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Srinivasa et al.

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(54) **WIRELESS DEVICE CALIBRATION FOR IMPLICIT TRANSMIT BEAMFORMING**

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(73) Assignee: **MARVELL INTERNATIONAL LTD.**, Hamilton (BM)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **14/875,305**

(22) Filed: **Oct. 5, 2015**

Related U.S. Application Data

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(51) **Int. Cl.**
G06F 11/00 (2006.01)
H04J 1/16 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H04W 24/02*** (2013.01); ***H04L 43/12*** (2013.01); *H04W 84/12* (2013.01)

(58) **Field of Classification Search**
CPC H04W 24/02; H04W 84/12; H04L 43/12
USPC 370/252, 328, 329, 254; 342/373
See application file for complete search history.

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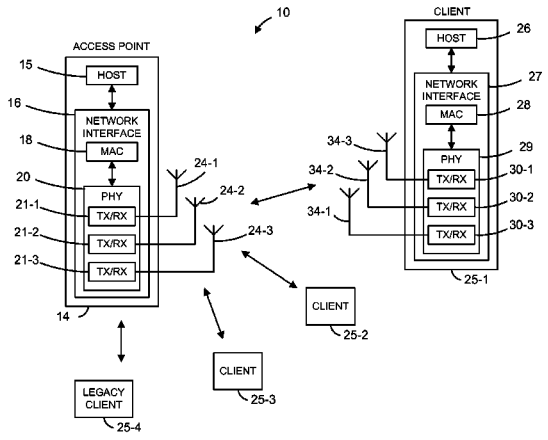
(Continued)

Primary Examiner — Chuong T Ho

(57) **ABSTRACT**

A first sounding packet is transmitted from the wireless communication device to a calibration station. A first channel descriptor is generated based on the first sounding packet. A second sounding packet is transmitted from the calibration station to the wireless communication device. A second channel descriptor is generated based on the second sounding packet. The first channel descriptor and the second channel descriptor are obtained at a processor device. Calibration coefficients indicative of one or both of phase imbalance and amplitude imbalance between a receive radio frequency (RF) chain and a transmit RF chain at the wireless communication device are generated based on the first and the second channel descriptors. The calibration coefficients are sent from the processor device to the wireless communication device.

28 Claims, 12 Drawing Sheets



(51) **Int. Cl.**

H04L 1/00	(2006.01)
H04L 12/26	(2006.01)
H04W 24/02	(2009.01)
H04W 84/12	(2009.01)

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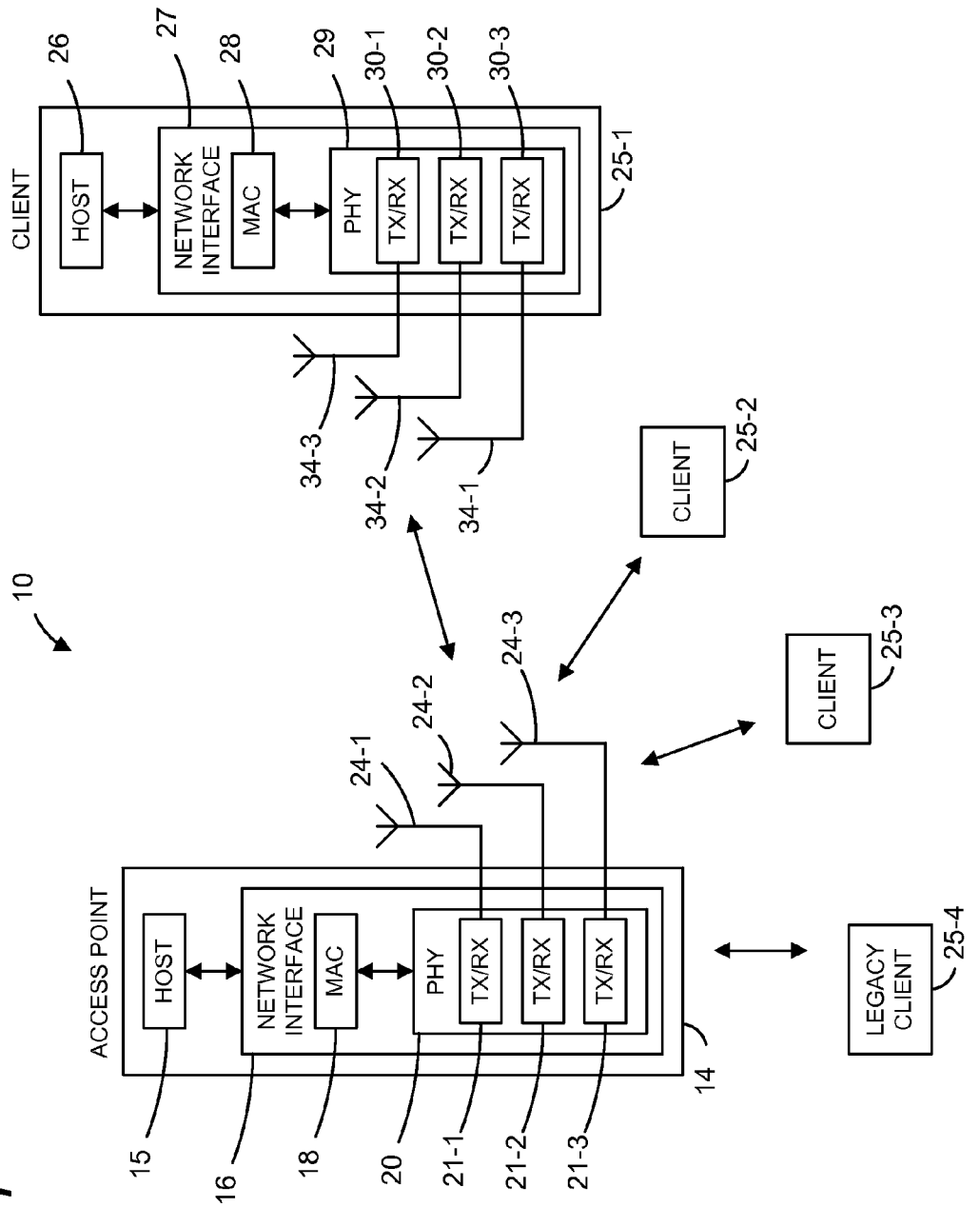

10
ACCESS POINT
HOST
NETWORK INTERFACE
MAC
PHY
TX/RX
TX/RX
TX/RX
14
15
16
18
20
21-1
21-2
21-3
24-1
24-2
24-3
CLIENT
25-1
26
27
28
29
30-1
30-2
30-3
34-1
34-2
34-3
CLIENT
25-2
CLIENT
25-3
LEGACY CLIENT
25-4

FIG. 1

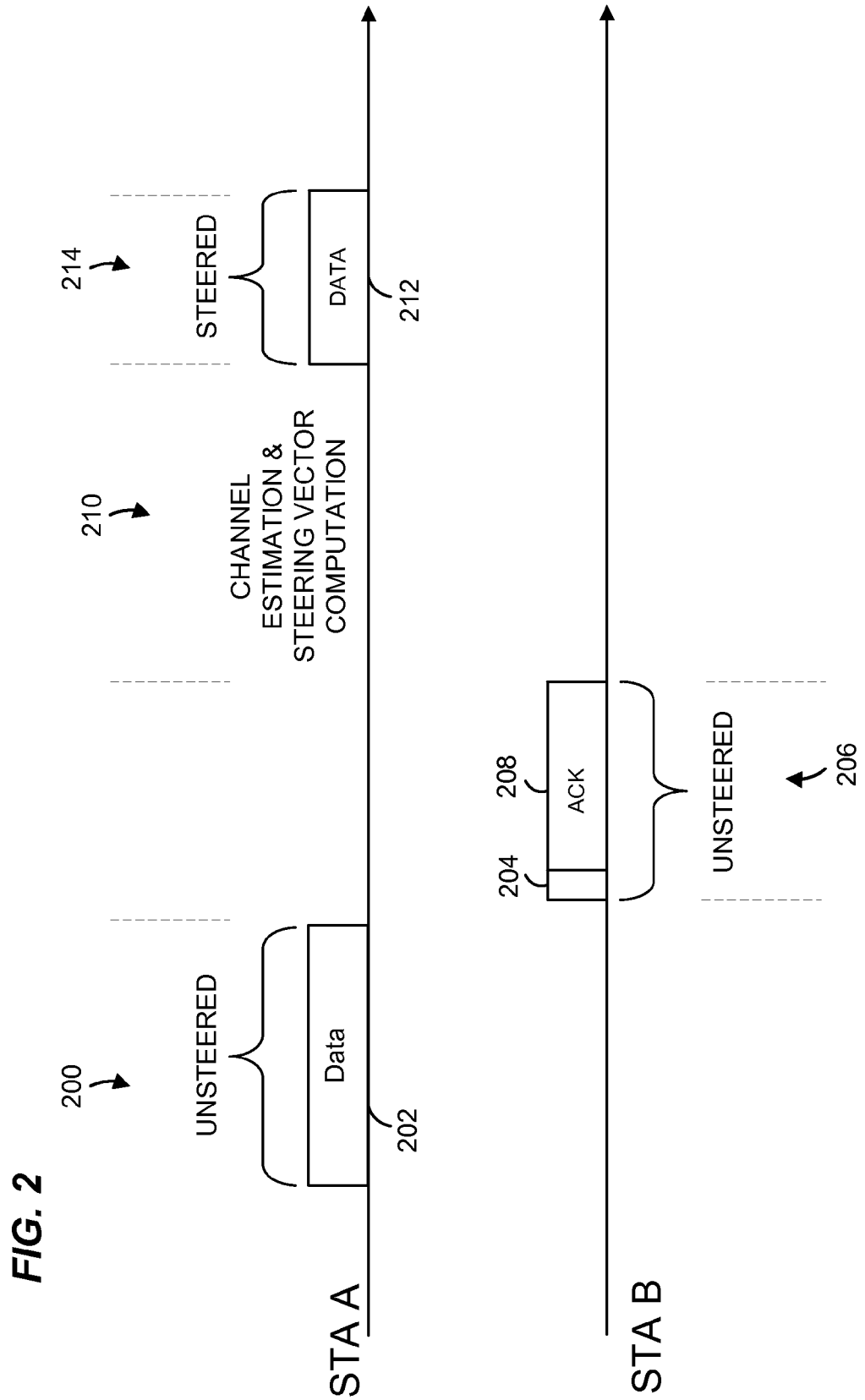

200
UNSTEERED
Data
202
STA A
210
CHANNEL ESTIMATION & STEERING VECTOR COMPUTATION
214
STEERED
DATA
212
204
208
ACK
UNSTEERED
206
STA B

FIG. 2

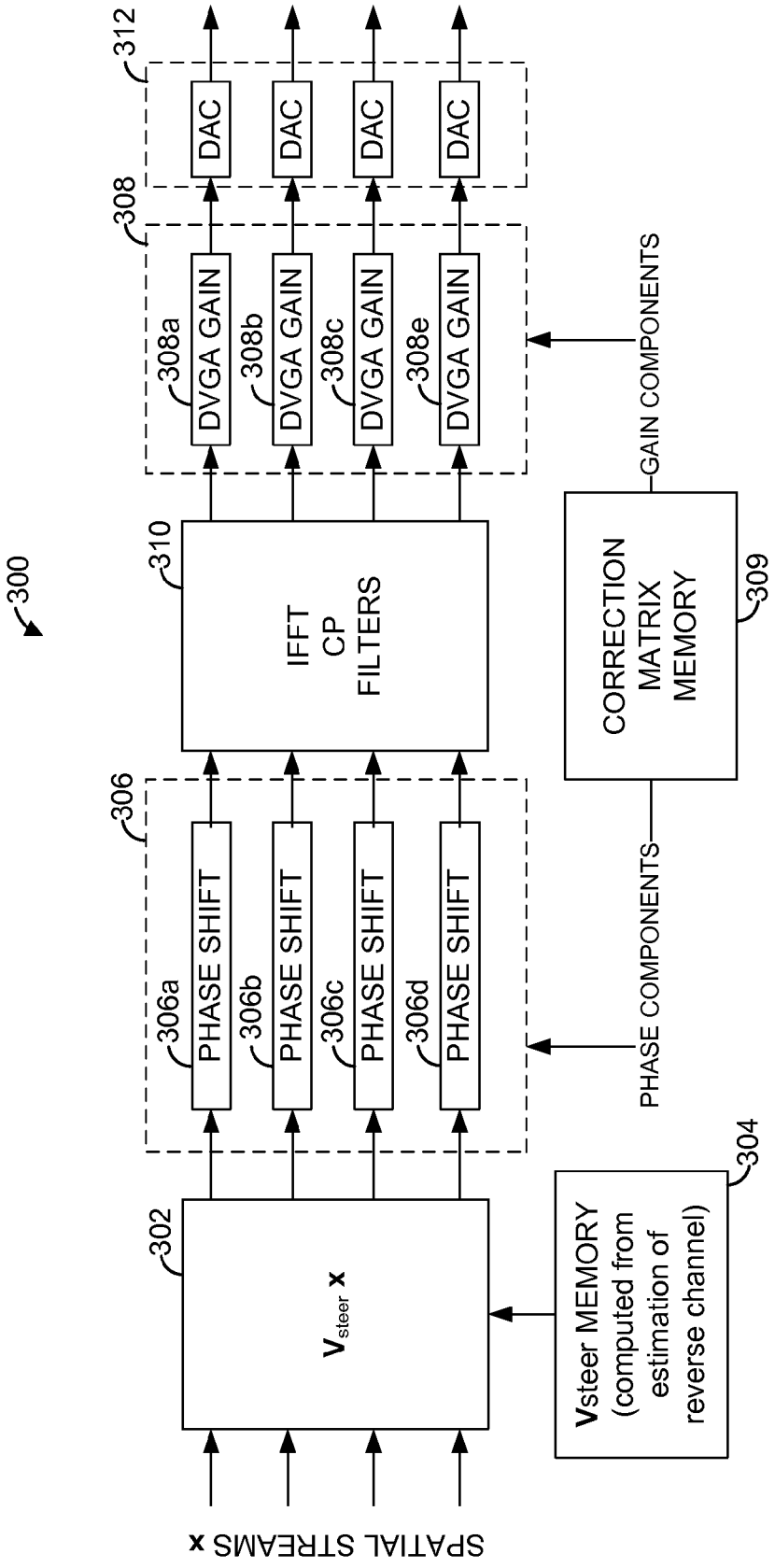

300
312
DAC
DAC
DAC
DAC
308
308a
DVGA GAIN
308b
DVGA GAIN
308c
DVGA GAIN
308e
DVGA GAIN
GAIN COMPONENTS
310
IFFT
CP
FILTERS
CORRECTION
MATRIX
MEMORY
309
306
306a
PHASE SHIFT
306b
PHASE SHIFT
306c
PHASE SHIFT
306d
PHASE SHIFT
PHASE COMPONENTS
302
V_{steer} x
Vsteer MEMORY
(computed from
estimation of
reverse channel)
304
SPATIAL STREAMS x

FIG. 3

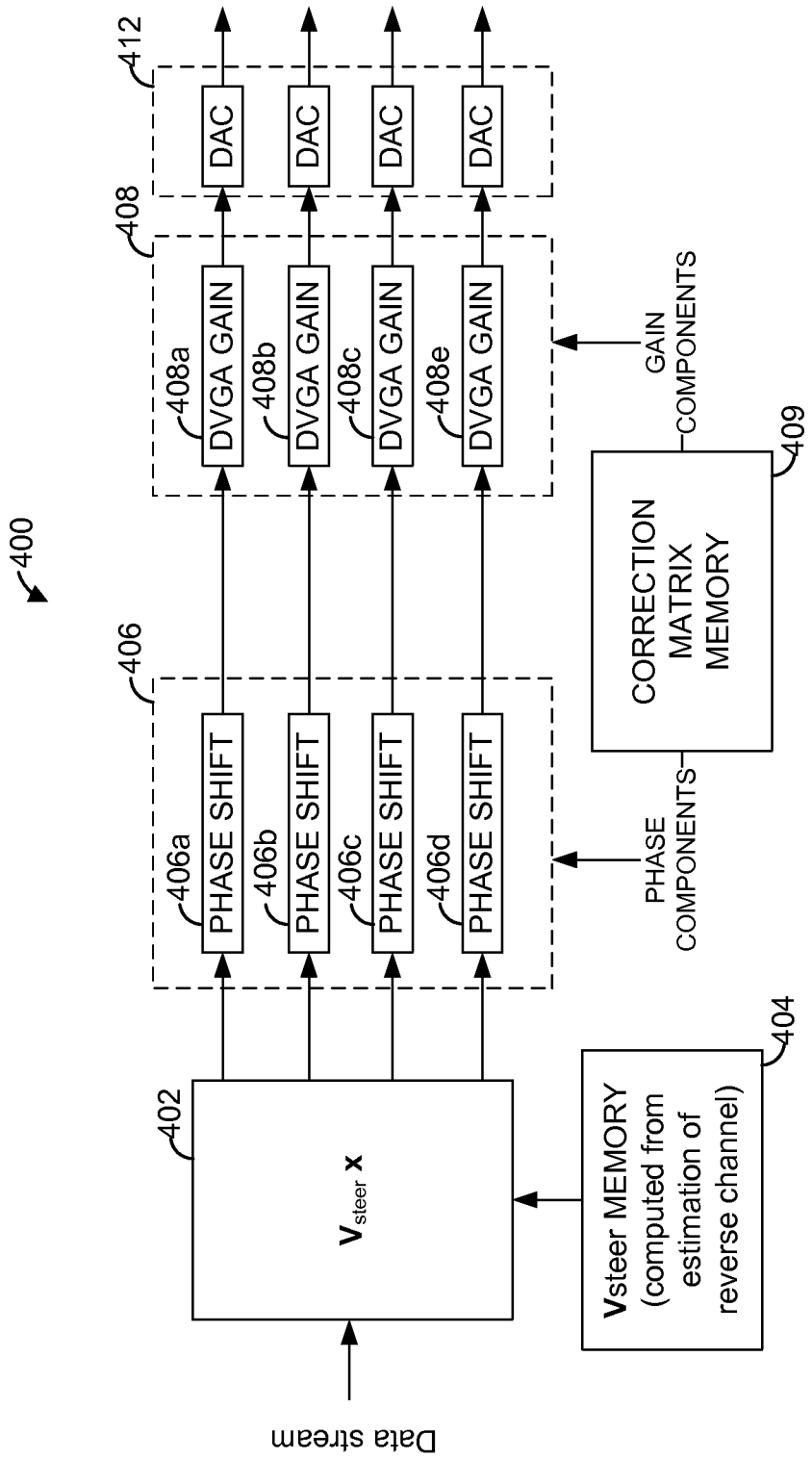

400
412
DAC
DAC
DAC
DAC
408
408a
DVGA GAIN
408b
DVGA GAIN
408c
DVGA GAIN
408e
DVGA GAIN
GAIN COMPONENTS
409
CORRECTION MATRIX MEMORY
406
406a
PHASE SHIFT
406b
PHASE SHIFT
406c
PHASE SHIFT
406d
PHASE SHIFT
PHASE COMPONENTS
404
Vsteer MEMORY (computed from estimation of reverse channel)
402
V_{steer} x
Data stream

FIG. 4

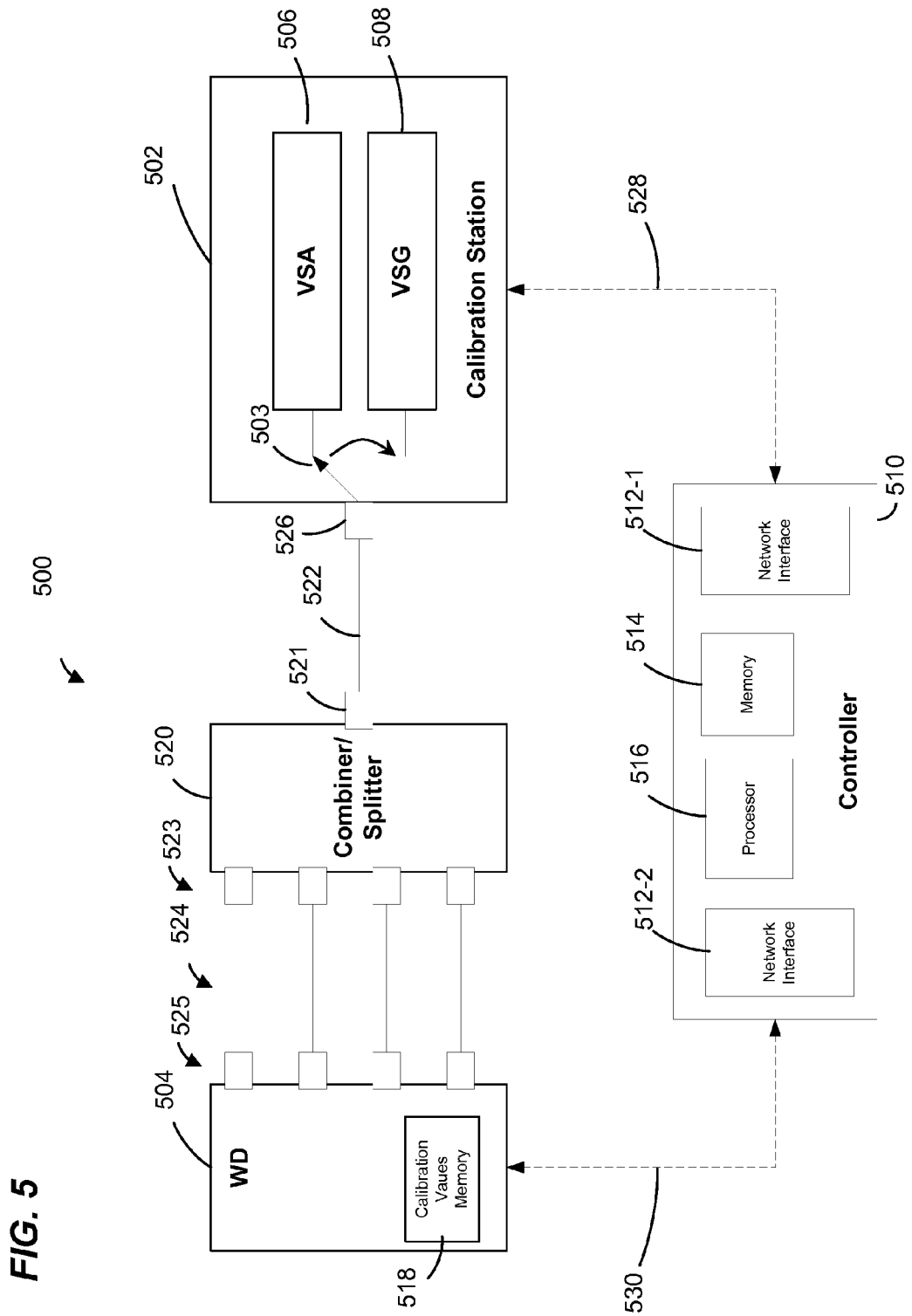

500
502
506
508
VSA
VSG
Calibration Station
503
526
522
521
528
510
512-1
Network Interface
514
Memory
516
Processor
512-2
Network Interface
Controller
520
Combiner/ Splitter
523
524
525
504
WD
Calibration Vaues Memory
518
530

FIG. 5

FIG. 6A

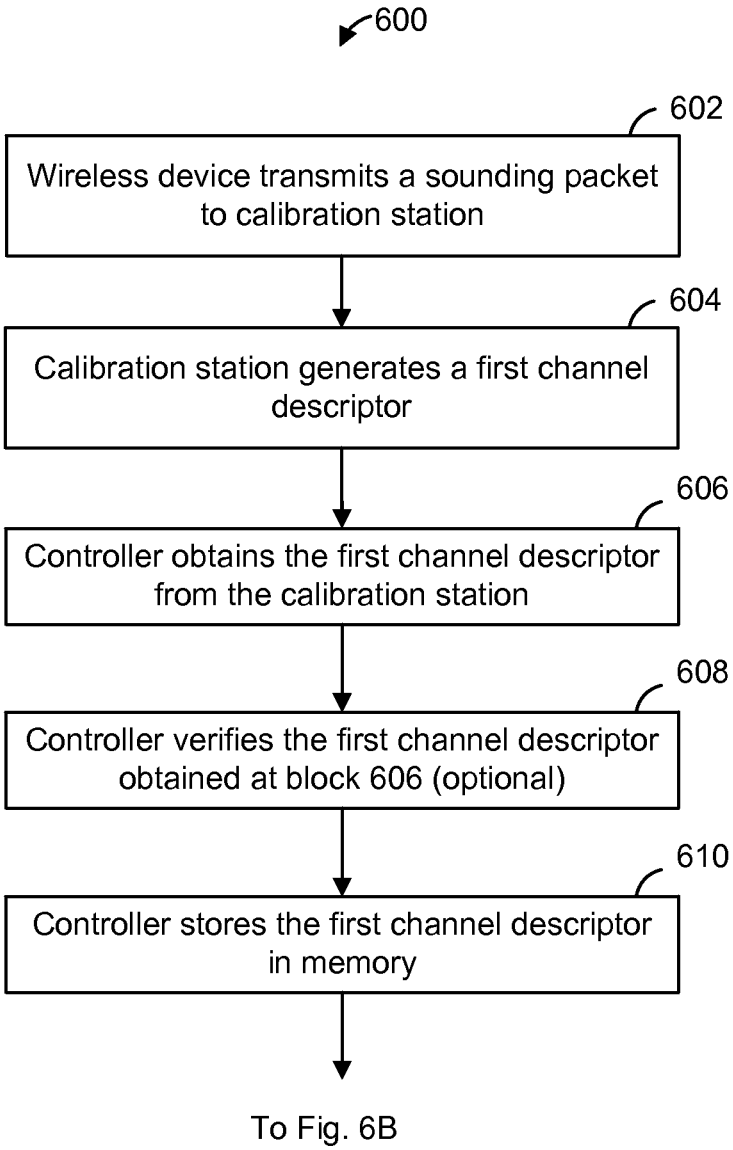

600
602
Wireless device transmits a sounding packet to calibration station
604
Calibration station generates a first channel descriptor
606
Controller obtains the first channel descriptor from the calibration station
608
Controller verifies the first channel descriptor obtained at block 606 (optional)
610
Controller stores the first channel descriptor in memory
To Fig. 6B

FIG. 6B

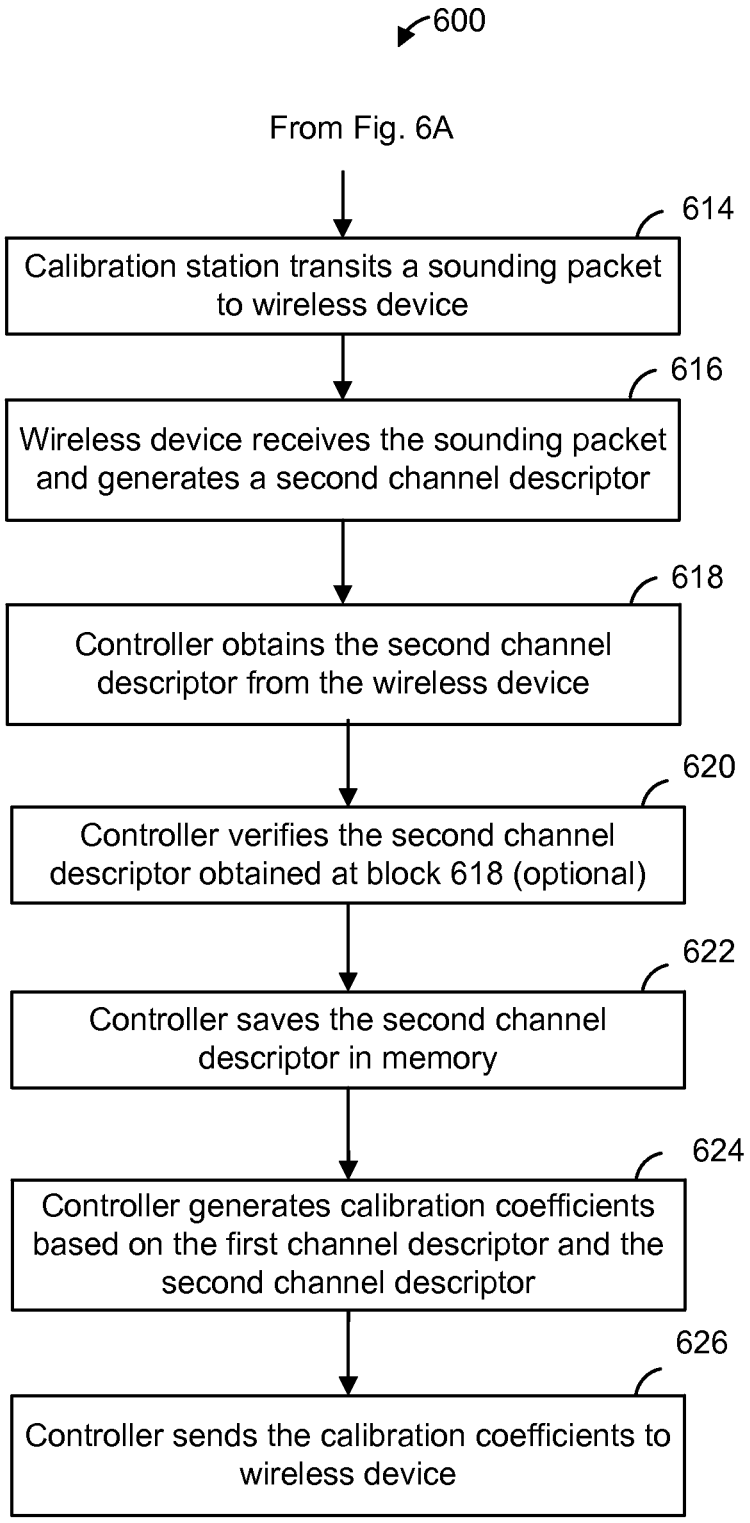

600
From Fig. 6A
614
Calibration station transits a sounding packet to wireless device
616
Wireless device receives the sounding packet and generates a second channel descriptor
618
Controller obtains the second channel descriptor from the wireless device
620
Controller verifies the second channel descriptor obtained at block 618 (optional)
622
Controller saves the second channel descriptor in memory
624
Controller generates calibration coefficients based on the first channel descriptor and the second channel descriptor
626
Controller sends the calibration coefficients to wireless device

FIG. 7

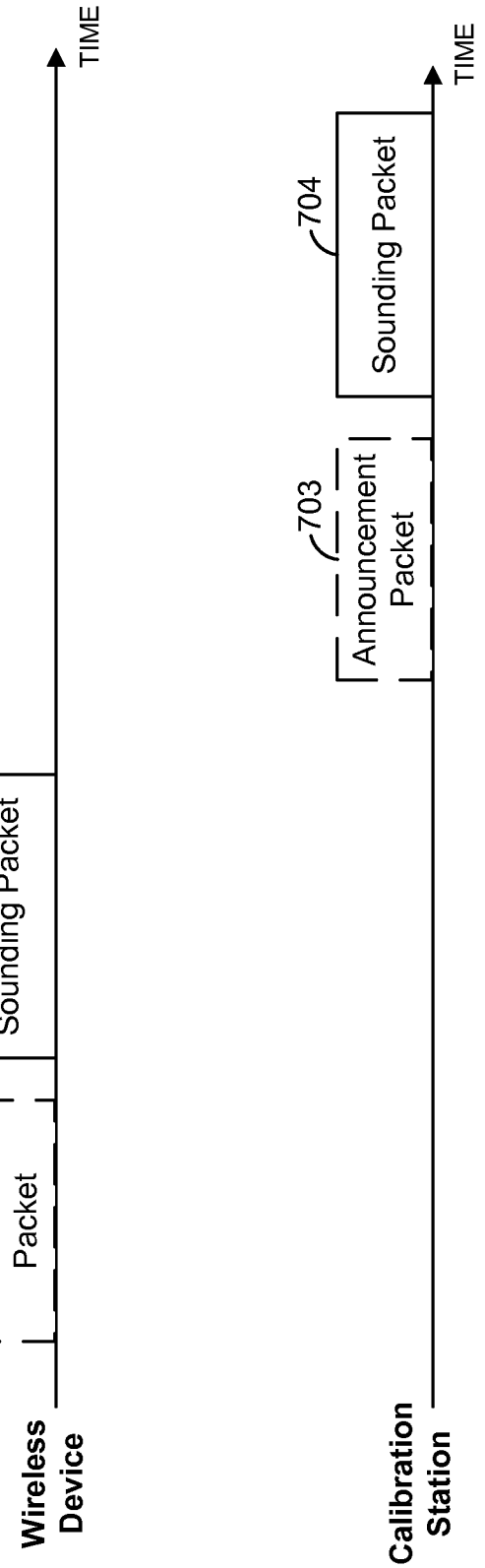

Wireless Device
TIME
701
Announcement Packet
702
Sounding Packet
Calibration Station
TIME
703
Announcement Packet
704
Sounding Packet

FIG. 8

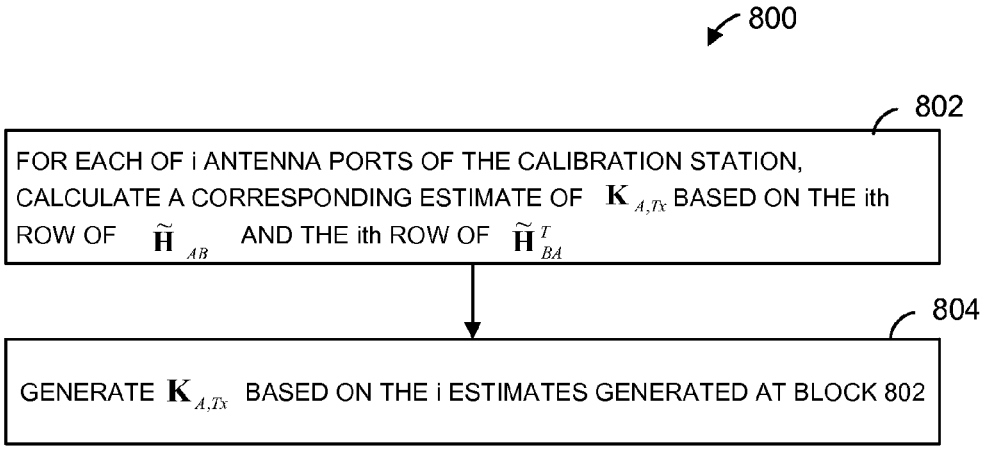

800
802
FOR EACH OF i ANTENNA PORTS OF THE CALIBRATION STATION, CALCULATE A CORRESPONDING ESTIMATE OF $\mathbf{K}_{A,Tx}$ BASED ON THE ith ROW OF $\tilde{\mathbf{H}}_{AB}$ AND THE ith ROW OF $\tilde{\mathbf{H}}_{BA}^{T}$
804
GENERATE $\mathbf{K}_{A,Tx}$ BASED ON THE i ESTIMATES GENERATED AT BLOCK 802

FIG. 9

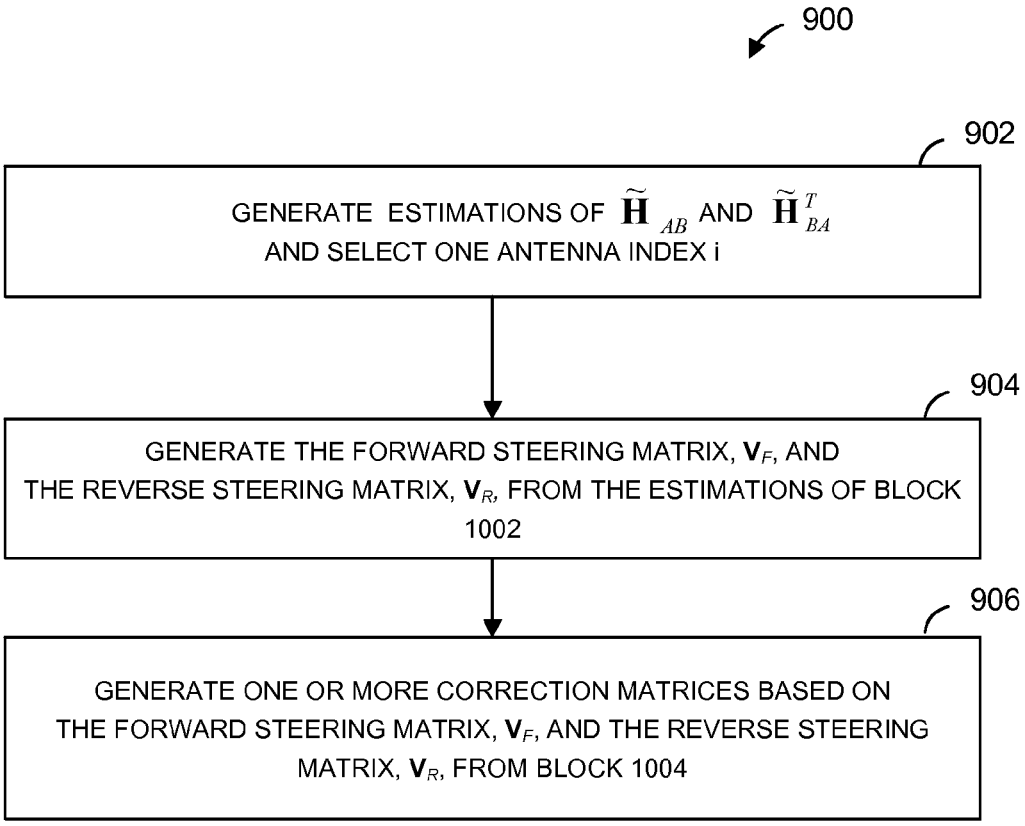

900
902
GENERATE ESTIMATIONS OF $\tilde{\mathbf{H}}_{AB}$ AND $\tilde{\mathbf{H}}_{BA}^{T}$ AND SELECT ONE ANTENNA INDEX i
904
GENERATE THE FORWARD STEERING MATRIX, $\mathbf{V}_F$, AND THE REVERSE STEERING MATRIX, $\mathbf{V}_R$, FROM THE ESTIMATIONS OF BLOCK 1002
906
GENERATE ONE OR MORE CORRECTION MATRICES BASED ON THE FORWARD STEERING MATRIX, $\mathbf{V}_F$, AND THE REVERSE STEERING MATRIX, $\mathbf{V}_R$, FROM BLOCK 1004

FIG. 10

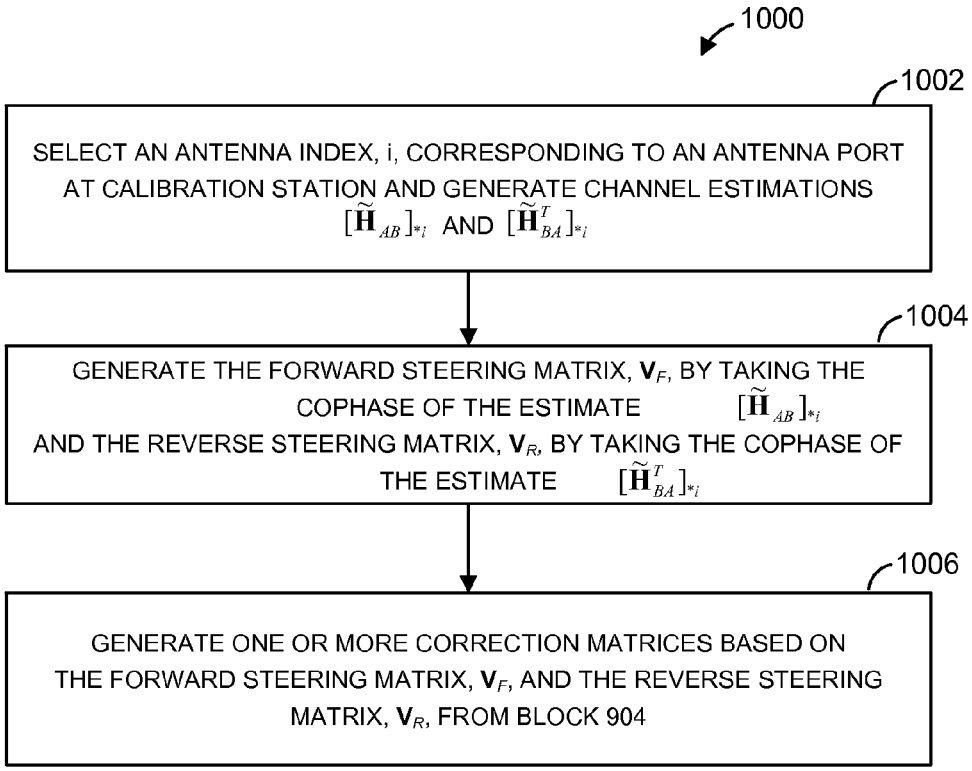
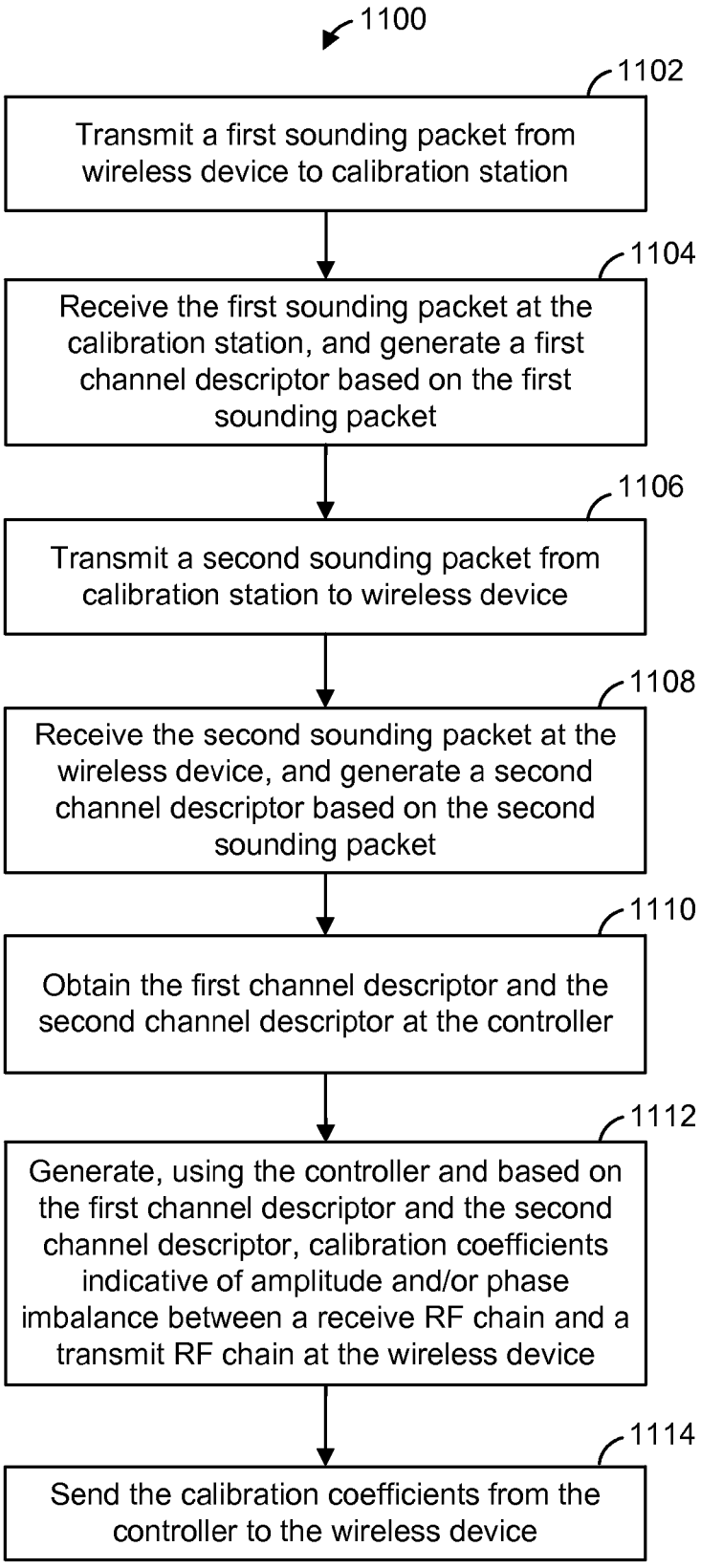

1000
1002
SELECT AN ANTENNA INDEX, i, CORRESPONDING TO AN ANTENNA PORT AT CALIBRATION STATION AND GENERATE CHANNEL ESTIMATIONS $[\widetilde{\mathbf{H}}_{AB}]_{*i}$ AND $[\widetilde{\mathbf{H}}^{T}_{BA}]_{*i}$
1004
GENERATE THE FORWARD STEERING MATRIX, $\mathbf{V}_F$, BY TAKING THE COPHASE OF THE ESTIMATE $[\widetilde{\mathbf{H}}_{AB}]_{*i}$ AND THE REVERSE STEERING MATRIX, $\mathbf{V}_R$, BY TAKING THE COPHASE OF THE ESTIMATE $[\widetilde{\mathbf{H}}^{T}_{BA}]_{*i}$
1006
GENERATE ONE OR MORE CORRECTION MATRICES BASED ON THE FORWARD STEERING MATRIX, $\mathbf{V}_F$, AND THE REVERSE STEERING MATRIX, $\mathbf{V}_R$, FROM BLOCK 904

FIG. 11


1100
1102
Transmit a first sounding packet from wireless device to calibration station
1104
Receive the first sounding packet at the calibration station, and generate a first channel descriptor based on the first sounding packet
1106
Transmit a second sounding packet from calibration station to wireless device
1108
Receive the second sounding packet at the wireless device, and generate a second channel descriptor based on the second sounding packet
1110
Obtain the first channel descriptor and the second channel descriptor at the controller
1112
Generate, using the controller and based on the first channel descriptor and the second channel descriptor, calibration coefficients indicative of amplitude and/or phase imbalance between a receive RF chain and a transmit RF chain at the wireless device
1114
Send the calibration coefficients from the controller to the wireless device

WIRELESS DEVICE CALIBRATION FOR IMPLICIT TRANSMIT BEAMFORMING

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 13/626,841, entitled "Wireless Device Calibration for Implicit Transmit Beamforming," filed on Sep. 25, 2012, which claims the benefit of U.S. Provisional Patent Application No. 61/540,999, filed on Sep. 29, 2011. The disclosures of both of the applications referenced above are incorporated herein by reference in their entireties.

FIELD OF TECHNOLOGY

The present disclosure relates generally to communication systems and, more particularly, to beamforming techniques used in such communication systems.

BACKGROUND

The background description provided herein is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent it is described in this background section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

In some wireless communication systems, one or more communication devices employ multiple antennas. Accordingly, a communication channel between two such devices can be a multiple-input, multiple-output (MIMO) channel when both communication devices employ multiple antennas, a single-input, multiple-output (SIMO) channel when a transmitting device ("the transmitter") employs a single transmit antenna and the receiving device ("the receiver") employs multiple receive antennas, or a multiple-input, single-output (MISO) channel when the transmitter employs multiple transmit antennas and the receiver employs a single receive antenna. Referring for simplicity to MIMO communication systems, transmission and reception properties in these systems can be improved by using each of the various transmit antennas to transmit the same signal while phasing (and amplifying) this signal as it is provided to the various transmit antennas to achieve beamforming or beamsteering. Generally speaking, beamforming or beamsteering creates a spatial gain pattern having one or more lobes or beams (as compared to the gain obtained by an omni-directional antenna) in one or more particular directions, while generally reducing the gain over that obtained by an omni-directional antenna in other directions. If the gain pattern is configured to produce a high gain lobe in the direction of each of the receiver antennas or in the direction of the receiver antennas in general, the MIMO system can obtain better transmission reliability between a particular transmitter and a particular receiver, over that obtained by single transmitter-antenna/receiver-antenna systems.

To conduct beamforming in the direction of a receiver, a transmitter generally utilizes a steering matrix determined based on specifics of the forward channel (i.e. the channel from the transmitter to the receiver) to condition the signals applied to various transmission antennas so as to produce the desired transmit gain pattern. In a technique known as explicit beamforming, to determine the specifics of the forward channel, such as the channel state information (CSI) or other measured description of the forward channel, the transmitter first sends training data to the receiver, which then determines or estimates forward channel specifics and/or a steering matrix that specifies beamsteering coefficients for steering signals from the transmitter in the direction of the receiver and then transmits this information back to the transmitter. In implicit beamforming, on the other hand, the transmitter determines specifics of the reverse channel (the channel from the receiver to the transmitter) based on training signals that the transmitter receives from the receiver and estimates the forward channel from the reverse channel by assuming channel reciprocity. However, radio frequency (RF) chain impairments in the form of gain/phase imbalances impair reciprocity between the forward and the reverse channel, and therefore, in implicit beamforming, the transmitter generally compensates for these RF chain imbalances in some manner (e.g., through calibration and/or correction) to achieve the desired transmission pattern.

Some explicit and implicit beamforming techniques as well as some calibration techniques are described in the IEEE 802.11n Draft Standard (2009), incorporated herein fully by reference.

SUMMARY

In one embodiment, a method of calibrating a wireless communication device includes receiving, at a calibration station, a first sounding packet, and generating, based on the first sounding packet, a first channel descriptor. The method additionally includes transmitting, from the calibration station to the wireless communication device, a second sounding packet. The method further obtaining, at a processor device, the first channel descriptor and a second channel descriptor, wherein the second channel descriptor is generated by the wireless communication device based on the second sounding packet. The method additionally includes generating, using the processor device and based on the first channel descriptor and the second channel descriptor, calibration coefficients indicative of one or both of (i) phase imbalance and (ii) amplitude imbalance between a receive radio frequency (RF) chain and a transmit RF chain at the wireless communication device. Also, the method includes sending the calibration coefficients from the processor device to the wireless communication device.

In another embodiment, a calibration system comprises a calibration station configured to receive a first sounding packet from a wireless communication device, generate a first channel descriptor based on the first sounding packet, and transmit a second sounding packet to the wireless communication device. The calibration system also comprises a processor device communicatively coupled to the calibration station and to the wireless communication device. The processor device is configured to obtain the first channel descriptor from the calibration station, obtain a second channel descriptor, wherein the second channel descriptor is generated by the wireless communication device based on the second sounding packet. The processor device is also configured to generate, based on the first channel descriptor and the second channel descriptor, calibration coefficients indicative of one or both of (i) phase imbalance and (ii) amplitude imbalance between a receive radio frequency (RF) chain and a transmit RF chain at the wireless communication device. Additionally, the processor device is configured to send the calibration coefficients from the processor device to the wireless communication device.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of an example wireless local area network (WLAN) in which devices calibrated according to procedures set forth in the present disclosure are utilized, according to an embodiment,

FIG. **2** is a diagram illustrating a specific example of a non-standard implicit beamforming technique, according to an embodiment,

FIG. **3** is a beamsteering unit used to apply a steering matrix and the determined correction matrix to the forward and/or reverse channels in a multi-carrier system, according to an embodiment,

FIG. **4** is a diagram of another beamsteering unit used to apply a steering matrix and the determined correction matrix to the forward and/or reverse channels in a single carrier system, according to another embodiment,

FIG. **5** is a diagram of a calibration system for calibrating a wireless device, according to an embodiment,

FIGS. **6**A and **6**B are flow diagrams illustrating an example calibration procedure conducted by a calibration system, according to an embodiment,

FIG. **7**, which is a timing diagram illustrating communications between a wireless device and a calibration station, according to an embodiment,

FIG. **8** is a flow diagram of an example method for generating calibration coefficients, according to an embodiment,

FIG. **9** is a flow diagram of an example method for generating calibration coefficients, according to another embodiment,

FIG. **10** is a flow diagram of an example method for generating calibration coefficients, according to yet another embodiment,

FIG. **11** is a flow diagram of an example method for calibrating a wireless communication device, according to an embodiment.

DETAILED DESCRIPTION

While the beamforming techniques described herein for processing and effecting a wireless data transmission are described as being used in communication systems that use one of the IEEE Standard 802.11 communication standards (e.g., IEEE 802.11n), these techniques may be used in various other types of wireless communication systems and are not limited to those conforming to one or more of the IEEE Standard 802.11 standards. For example, these techniques may be used in communications based on the IEEE 802.16e, 802.16j, or 802.16m standards (known as "WiMAX") and others.

FIG. **1** is a block diagram of an example wireless local area network (WLAN) **10** in which devices calibrated according to procedures set forth in the present disclosure are utilized, according to an embodiment. An access point (AP) **14** includes a host processor **15** coupled to a network interface **16**. The network interface **16** includes a medium access control (MAC) processing unit **18** and a physical layer (PHY) processing unit **20**. The PHY processing unit **20** includes a plurality of transceivers **21**, and the transceivers **21** are coupled to a plurality of antennas **24**. Although three transceivers **21** and three antennas **24** are illustrated in FIG. **1**, the AP **14** includes different numbers (e.g., 1, 2, 4, 5, etc.) of transceivers **21** and antennas **24** in other embodiments. In one embodiment, the MAC processing unit **18** and the PHY processing unit **20** are configured to operate according to a first communication protocol (e.g., the IEEE 802.11n Standard) which supports certain frame exchanges and other procedures specifically related to explicit and/or implicit beamforming. In another embodiment, the MAC processing unit **18** and the PHY processing unit **20** are alternatively or additionally configured to operate according to a second communication protocol, which does not explicitly support beamforming (e.g., the IEEE 802.11g Standard, the IEEE 802.11a Standard, etc.). The second communication protocol is herein referred to as a "legacy protocol."

The WLAN **10** includes a plurality of client stations **25**. Although four client stations **25** are illustrated in FIG. **1**, the WLAN **10** includes different numbers (e.g., 1, 2, 3, 5, 6, etc.) of client stations **25** in various scenarios and embodiments. At least one of the client stations **25** (e.g., client station **25-1**) is configured to operate at least according to the first communication protocol. The WLAN **10** also includes a client station **25-4** that is not configured to operate according to the first communication protocol but is configured to operate according to a legacy protocol, in some embodiments. Accordingly, the client station **25-1** does not explicitly support frame exchanges or other procedures specifically related to beamforming. Such a client station **25-4** is referred to herein as a "legacy client station." In some embodiments and/or scenarios, the WLAN **10** includes more than one legacy client station. In other embodiments and/or scenarios, the WLAN **10** includes no legacy client stations.

The client station **25-1** includes a host processor **26** coupled to a network interface **27**. The network interface **27** includes a MAC processing unit **28** and a PHY processing unit **29**. The PHY processing unit **29** includes a plurality of transceivers **30**, and the transceivers **30** are coupled to a plurality of antennas **34**. Although three transceivers **30** and three antennas **34** are illustrated in FIG. **1**, the client station **25-1** includes different numbers (e.g., 1, 2, 4, 5, etc.) of transceivers **30** and antennas **34** in other embodiments.

In an embodiment, one or more of the client stations **25-2**, **25-3**, and **25-4** have a structure the same as or similar to the client station **25-1**. In these embodiments, the client stations **25** which are structured the same as or similar to the client station **25-1** have the same or a different number of transceivers and antennas. For example, the client station **25-2** has only two transceivers and two antennas, according to an embodiment.

In an embodiment, the AP **14** utilizes implicit beamforming for communication with one or more of the client stations **25** in order to increase signal directivity and generally improve quality (e.g., SNR) of the signals received by the client stations. In implicit beamforming, the AP **14** determines the channel state information (CSI) or other measured description of the reverse channel (i.e., the channel from a particular client station, such as the client station **25-1**, to the AP **14**) from the training signal(s) sent from, for example, the client station **25-1** to the AP **14** thereby avoiding the multiple communications between the AP **14** and the client station **25-1** generally required in explicit beamforming. Further, according to an embodiment, the AP **14** utilizes implicit beamforming for communication with the client station **25-4** (a legacy client station) which does not support frame exchanges generally required for beamforming, according to an embodiment.

To conduct implicit beamforming, according to one embodiment, the AP **14** implements a "standard" implicit beamforming technique. In this embodiment, the AP **14** transmits to the client station **25-1** a data unit that includes a request to transmit a sounding frame that "sounds" the reverse channel from the client station **25-1** to the AP **14** thereby allowing the AP **14** to fully determine or estimate characteristics of the reverse channel (e.g., to determine CSI or other

measured description of the reverse channel). The AP **14** then computes an estimate of the forward channel (i.e., the channel from the AP **14** to the client station **25-1**) based on the estimate of the reverse channel by assuming channel reciprocity and, based on the forward channel estimate, generates a steering matrix specifying the beamsteering coefficients that are then applied to the signals to be transmitted to the client station **25-1** to produce the desired transmit gain pattern at the transmitter output.

Alternatively, in another embodiment, the AP **14** conducts implicit beamforming by implementing a "non-standard" implicit beamforming. According to this embodiment, the AP **14** determines an estimate of the reverse channel based on a data unit received from the client station **25-1**, wherein the received data unit is not specifically related to beamforming (e.g., a non-sounding data unit, also referred to herein as a "regular" data unit). More specifically, in this embodiment, the AP **14** receives from the client station **25-1** a regular data unit that does not specifically sound the channel but nonetheless includes training signals (e.g., in a preamble) that allow the AP **14** to determine or estimate characteristics of the reverse channel. Similar to the case of standard implicit beamforming, the AP **14** then computes an estimate of the forward channel from the estimate of the reverse channel by assuming channel reciprocity, and, based on the forward channel estimate, computes a steering matrix to be used for beamforming in the direction of the client station **25-1**, according to an embodiment.

FIG. **2** is a diagram illustrating one specific example of a non-standard implicit beamforming technique, according to an embodiment. In FIG. **2**, Station A is a "beamformer" or a device that transmits or will transmit a data unit using a steering matrix, and Station B is a "beamformee" or a device that receives a data unit transmitted using a steering matrix. Referring to FIG. **1**, according to one embodiment, the AP **14** is the beamformer, and the client station **25-1** is the beamformee. In another embodiment, the client station **25-1** is the beamformer, and the AP **14** is the beamformee.

During a time interval **200**, Station A transmits an unsteered data unit **202** (i.e., a data unit that is transmitted omni-directionally (as used herein, the term "omni-directional" encompasses the term "pseudo-omni-directional")) to Station B. In an embodiment, the data unit **202** includes an acknowledge (ACK) request that instructs the Station B to transmit an ACK frame upon successful reception of the data unit **202**. Accordingly, in response to receiving the data unit **202**, Station B transmits an ACK frame **208** to the Station A, wherein the ACK frame includes several training signal fields in a portion **204**. In particular, as each training field is transmitted, Station B applies a different mapping of symbols to spatial streams, according to an embodiment. In an embodiment, the number of training fields corresponds to the number of spatial streams used for modulating data units transmitted from Station B to Station A which depends on the particular modulation and coding scheme (MCS) used for communication between Station A and Station B.

During a time interval **210**, Station A estimates the MIMO channel in the direction from Station B to Station A (i.e., the reverse channel) based on the training fields of the received ACK frame **208**. Station A then generates an estimate of the forward channel using the estimate of the reverse channel and generates a steering matrix for use in forward channel transmissions. As illustrated in FIG. **2**, during a time period **214**, Station A transmits a data unit **212** using the steering matrix generated in the interval **210**.

In some embodiments, the non-sounding data frame used by the Station A to estimate the reverse channel is a data unit other than an ACK frame or a negative acknowledgement (NACK) frame, i.e., a frame that acknowledges successful receipt of a previous frame, or a frame that indicates unsuccessful receipt of a previous frame, respectively. For example, the non-sounding data frame used by the Station A to estimate the reverse channel is a data unit that carries user data, in some embodiments and/or scenarios. Generally, Station A utilizes any suitable non-sounding data unit received from Station B to generate an estimate of the reverse channel as long as the received data unit includes at least one training signal, in various embodiment and/or scenarios.

Referring again to FIG. **1**, in one embodiment, the AP **14** implements a non-standard implicit beamforming technique when communicating with a legacy client station (e.g., client station **25-4**) that does not support certain procedures required for standard explicit or implicit beamforming. For example, the client station **25-4** is not configured to process a request to transmit a sounding frame, according to some embodiments. In some such embodiments, the regular data unit used to estimate the reverse channel includes training data that allows the AP **14** to only partially estimate the reverse channel. In one such embodiment, for example, the client station **25-4** includes three antennas but transmits a data unit to the AP **14** via only two of the antennas (i.e., via two spatial streams). This data unit, therefore, includes training signals that allow the AP **14** to only determine a partial channel estimate (in this case at most a two-dimensional channel estimate). In this embodiment, the AP **14** then utilizes the partial channel estimate to generate a steering matrix which results in at least some channel directivity in the direction of the client station **25-4**.

As discussed above, to conduct implicit beamforming, such as standard or non-standard implicit beamforming, the AP **14** assumes channel reciprocity to determine an estimate of the forward channel based on an estimate of the reverse channel, according to an embodiment. However, channel estimation is generally conducted at baseband, and therefore, the observed channel contains the equivalent RF responses of the transmit and the receive chains which, according to an embodiment, are not identical in the same device. In this embodiment, channel reciprocity is therefore impaired. To reduce or account for the errors introduced by RF chain impairments in an implicit beamforming technique, in one embodiment, the AP **14** applies a correction matrix to the signals to be transmitted (i.e., the output signals) during the beamforming process to compensate for measured differences between the actual forward and reverse channels. In particular, this technique first determines a correction matrix that at least partially compensates for RF impairments caused by transmit and receive chain imbalance in the communication device. Then, each time a new steering matrix is to be calculated for the forward channel, the beamforming technique applies the correction matrix to a steering matrix determined using a basic implicit beamforming technique, such as a standard or a non-standard implicit beamforming technique, so that, once the correction matrix is determined, the transmitter performs implicit beamforming using a measured description of the reverse channel to produce an estimate of the forward channel. Alternatively, in some embodiments, the transmitter calculates correction matrices for its receive chains, so that once the correction matrix is determined, the transmitter applies the correction matrices to the reverse channel estimation, and performs implicit beamforming using a measured description of this processed reverse channel estimate to produce an estimate of the forward channel. In an embodiment, the calibration procedure is conducted infrequently, compared with steering matrix updates. For

example, in one embodiment, the calibration procedure is conducted only prior to deployment of a device, for example during manufacturing of the device (or of a relevant portion of the device), and the determined correction matrix is then stored in a memory of the device to be later used to compensate for RF chain imbalance when implicit beamforming is performed by the device.

Referring to FIG. **1**, in mathematical terms, the channel between the AP **14** (Station A) and a client station such as, for example, the client station **25-1** (Station B) is generally characterized by:

$$y_B=\tilde{H}_{AB}Q_Ax_A+n_B \quad \text{(Equation 1)}$$

where y_B and n_B are the received signal vector and additive noise vector at Station B, respectively; $\tilde{H}_{AB}$ is the equivalent channel from Station A to Station B; x_A is the signal vector to be transmitted from Station A; and Q_A is the steering matrix (which may be a vector) at Station A. In various embodiments and/or scenarios, the steering matrix Q_A is determined based on the current channel state information (CSI) for the channel between Station A and Station B. For example, the steering matrix Q_A is determined using an explicit beamforming technique or an implicit beamforming technique such as described above in various embodiments and/or scenarios.

As discussed above, in implicit beamforming techniques, the AP **14** determines an estimate for the forward channel based on an estimate of the reverse channel under the assumption of channel reciprocity. In the case of time-division duplexing (TDD), the forward link and the reverse link share the same frequency band, so their physical propagation channels, denoted as H_{AB} and H_{BA} respectively, can be assumed reciprocal ($H_{AB}=H_{BA}^T$), if the channel is varying slowly compared to the interval between forward and reverse link transmissions. Further, in the case of an orthogonal frequency division multiplexing (OFDM) system, according to an embodiment, channel estimation is conducted for each subcarrier, or for a group of adjacent subcarriers, and channel reciprocity is assumed for the forward and the reverse channels at each subcarrier frequency.

However, as discussed above, the actual channels observed at baseband also include the equivalent RF responses of the transmit and receive chains, which is not identical for the transmit and receive chains in the same device, according to some embodiments. In these embodiments, this imbalance results in the equivalent channels $\tilde{H}_{AB}$ and $\tilde{H}_{BA}$ not being reciprocal. In an embodiment, the mathematical description of this imbalance issue is represented as:

$$\tilde{H}_{AB}=C_{B,Rx}H_{AB}C_{A,Tx}, \quad \text{(Equation 2)}$$

where $C_{B,Rx}$ represents the RF responses at the receive chains of Station B; and where $C_{A,Tx}$ represents the RF responses at the transmit chains of Station A. By ignoring the coupling among transmit and receive chains, the matrices $C_{B,Rx}$ and $C_{A,Tx}$ are approximately modeled, in an embodiment, as diagonal matrices.

The equivalent channel from Station B to Station A, $\tilde{H}_{BA}$, according to an embodiment, is represented as:

$$\tilde{H}_{BA}=C_{A,Rx}H_{AB}^TC_{B,Tx} \quad \text{(Equation 3)}$$

Due to imbalances between the transmit and receive chains at Station A and at Station B, respectively, i.e., $C_{A,Tx}\neq C_{A,Rx}^T$ and/or $C_{B,Tx}\neq C_{B,Rx}^T$ it stands that $\tilde{H}_{AB}\neq\tilde{H}_{BA}^T$.

In some embodiments, one or both devices compensate the transmit and/or the receive RF imbalance at baseband. For example, one or more correction matrices are calculated and then multiplied with the transmitted or received signal vector in the baseband to correct the imbalance and maintain reciprocity between the transmit and receive channels, according to some embodiments and/or scenarios. For example, in one embodiment, a transmitter-side correction matrix $K_{A,Tx}$ and a receiver-side correction matrix $K_{B,Rx}$ are calculated such that they completely compensate for the imbalance. Thus, in this embodiment, a corrected equivalent channel from Station A to Station B H_{AB} is then represented as:

$$\hat{H}_{AB}=K_{B,Rx}\tilde{H}_{AB}K_{A,Tx}=\alpha\tilde{H}_{BA}^T, \quad \text{(Equation 4)}$$

where α is a scalar. Equation 4 is indicative of a "strict reciprocity system", i.e., a system that offers full calibration at both the transmitter and receiver. To implement a strict reciprocity system, in an embodiment, Station A left-multiplies the correction matrix $K_{A,Tx}$ with the signal it is to transmit (Q_Ax_A) at baseband. Also, in this embodiment, upon receiving the signal, Station B left-multiplies the correction matrix $K_{B,Rx}$ with the received signal at baseband.

Alternatively, in another embodiment, only transmitter-side compensation is utilized. In this embodiment, $\hat{H}_{AB}$ is represented as, for example:

$$\hat{H}_{AB}=\tilde{H}_{AB}K_{A,Tx}=D_B\tilde{H}_{BA}^T, \quad \text{(Equation 5)}$$

where D_B is a diagonal matrix representing the RF imbalance at Station B. Equation 5 is therefore indicative of a "semi-reciprocal system", in this case, because it offers partial calibration, or calibration only on the transmitter side. To implement a semi-reciprocal system, Station A left-multiplies the correction matrix $K_{A,Tx}$ with the signal it is to transmit (Q_Ax_A) at baseband, according to an embodiment. Upon receiving the signal, in this embodiment, Station B does not apply a correction matrix, such as the correction matrix $K_{B,Rx}$ with the received signal.

In some embodiments, the transmitter-side compensation is also applied at the receiver chains of the same device. That is, in these embodiments, to realize semi-reciprocity, Station A left-multiplies the correction matrix $K_{A,Rx}$ with the reverse channel estimates at baseband:

$$\hat{H}_{BA}=K_{A,Rx}\tilde{H}_{BA} \quad \text{(Equation 6)}$$

so,

$$\hat{H}_{AB}=D_B\tilde{H}_{BA}^T \quad \text{(Equation 7)}$$

where $K_{A,Rx}=\text{inv}(K_{A,Tx})$. Similar to Equation 5, D_B in Equation 7 is a diagonal matrix representing the RF imbalance at station B.

Further, in some embodiments, the gain mismatch between the receive and the transmit RF chains is small, and RF imbalance compensation is accomplished by only compensating for the phase imbalance. Accordingly, in one such embodiment in which compensation is performed on the transmit side, $\hat{H}_{AB}$ is then expressed as:

$$\hat{H}_{AB}=\tilde{H}_{AB}K_{A,TX}=\tilde{H}_{AB}\begin{bmatrix} e^{j\theta_1} & & & \\ & e^{j\theta_2} & & \\ & & \ddots & \\ & & & e^{j\theta_N} \end{bmatrix} \quad \text{(Equation 8)}$$

FIG. **3** is a diagram of a beamsteering unit **300** used to apply a steering matrix and the determined correction matrix to the forward and/or reverse channels in a multi-carrier system (e.g., as defined in the IEEE 802.11n Standard or any other multi-carrier based communication protocol), according to an embodiment. Referring to FIG. **1**, the AP **14** and the client station **25-1**, in one embodiment, each include a beam-

steering unit such as the beamsteering unit **300**. In the description below, the AP **14** is a beamformer (Station A) and the client station **25-1** is a beamformee (Station B). In some embodiments, however, the client station **25-1** is the beamformer and the AP **14** is the beamformee.

The spatial streams, x, are provided to a beamsteering matrix controller **302** (controller **302**), which applies the computed steering matrix V_{steer} (beamsteering matrix V_{steer}), computed as discussed above and stored in a memory **304**. When compensating only the phase differences among the antennas on the Station A, the controller **302** provides output signals to a phase correction stage **306** (stage **306**), which then applies different phase shifts for each of the output signals, as determined by a correction matrix ($K_{A,Tx}$) stored in a memory **309**, e.g., by using only phase components of the correction matrix. In some embodiments, the correction matrix is expressed in terms of gain and phase, whereas in other embodiments the correction matrix is expressed only in terms of phase. In an embodiment, the stage **306** is implemented by different phase shifter stages **306***a*-**306***d*, one for each transmitter chain.

In the illustrated embodiment, correction of the phase shift is determined in the frequency domain. The correction occurs at the transmitter of Station A, as shown, or in other examples, at the receiver of Station B. At the transmitter side, according to an embodiment, the correction is performed on each sub-carrier at each transmitter chain, after the beamsteering matrix, V_{steer} has been applied to the spatial stream, x.

In some embodiments, Station A also compensates for gain mismatches, by using a gain correction stage **308** implemented, for example, using a digital variable gain amplifier (DVGA). The stage is implemented by different DVGA gain stages **308***a*-**308***d*, one for each transmit chain, in the illustrated example. In an embodiment, the gain correction stage applies digital gain with correction values, from the correction matrix, to each transmitter chain, where the corresponding matrix multiplication is done in $K_{A,Tx}$, the time domain. In the illustrated example, a processor **310** includes an inverse discrete Fourier transform calculator, e.g., an inverse fast Fourier transform (IFFT) calculator, that converts the phase corrected signal of stage **306** from the frequency domain to the time domain for the gain correction stage **308**. Additionally, the processor **310** includes a cyclic prefix (CP) inserter to insert a CP in OFDM symbols to be transmitted. In some embodiments, the processor **310** also includes one or more filters. A corresponding digital-to-analog converter (DAC) **312** generates the corrected signal stream for transmission via a corresponding antenna of Station A.

In some configurations, a MIMO-OFDM transmitter applies time domain cyclic delay diversity (TCDD) after the IFFT and CP insertion performed by the processor **310** on the transmit signals. In some calibration procedures, the Station A turns OFF the TCDD function whenever sending a calibration initiation (e.g. sounding) packet and whenever Station A transmits the steered data packets determined using an implicit beamforming technique. If Station A does not turn OFF TCDD, then in other embodiments and/or scenarios Station A manually applies the TCDD effects (i.e., linear phase shifts across sub-carriers) in the frequency domain of the channel estimations on the packets of the reverse channel.

FIG. **4** is a diagram of another example beamsteering unit **400** used to apply a steering matrix and the determined correction matrix to the forward and/or reverse channels in a single carrier system (e.g., as defined by the IEEE 802.11b Standard or any other single-carrier based communication protocol), according to another embodiment. Referring to FIG. **1**, the AP **14** and the client station **25-1**, in one embodiment, each include a beamsteering unit such as the beamsteering unit **400**. In the description below, the AP **14** a beamformer (Station A) and the client station **25-1** is a beamformee Station B. In some embodiments, however, the client station **25-1** is the beamformer and the AP **14** is the beamformee.

The beamsteering unit **400** is similar to the beamsteering unit **300** of FIG. **3** except that in the beamsteering unit **400** the beamsteering matrix V_{steer} is applied to a single-carrier data stream. Accordingly, in the beamsteering unit **400**, a phase shift correction is applied in the time domain rather than the frequency domain. The time-domain correction occurs at the transmitter of Station A, as shown, or in other examples, at the receiver of (Station B). At the transmitter side, the correction is performed at each transmitter chain, after the beamsteering matrix V_{steer}, has been applied to the spatial stream, x.

Similar to operation of the beamsteering unit **300** of FIG. **3**, in the beamsteering unit **400**, the spatial streams, x, are provided to a beamsteering matrix controller **402** (controller **402**), which applies the computed steering matrix V_{steer} (beamsteering matrix V_{steer}), computed as discussed above and stored in a memory **404**. When compensating only the phase differences among the antennas on the Station A, the controller **402** provides output signals to a phase correction stage **406** (stage **406**), which then applies different phase shifts for each of the output signals, as determined by a correction matrix ($K_{A,Tx}$) stored in a memory **409**, e.g., by using only phase components of the correction matrix. In some embodiments, the correction matrix is expressed in terms of gain and phase, whereas in other embodiments the correction matrix is expressed only in terms of phase. In an embodiment, the stage **406** is implemented by different phase shifter stages **406***a*-**406***d*, one for each transmitter chain.

In some embodiments, Station A also compensates for gain mismatches, by using a gain correction stage **408** implemented, for example, using a digital variable gain amplifier (DVGA). The stage is implemented by different DVGA gain stages **408***a*-**408***d*, one for each transmit chain, in the illustrated example. The gain correction stage applies digital gain with correction values, from the correction matrix, $K_{A,Tx}$, to each transmitter chain, where the corresponding matrix multiplication is done in the time domain, according to an embodiment. A corresponding DAC **412** generates the corrected signal stream for transmission via a corresponding antenna of Station A.

FIG. **5** is a diagram of a calibration system **500** for calibrating wireless device, such as a wireless device (WD) **504**, according to an embodiment. The calibration system **500** includes a calibration station **502** and a controller **510**. In an embodiment, the calibration station **502** is a MIMO test system capable of generating and analyzing signals conforming to one or more communication standards. The calibration station **502** includes one or several input/output ports **526**. Depending on the operating mode of the calibration station **502**, each of the input/output ports **526** transits or receives communication signals conforming to a certain communication protocol, such as an IEEE 802.11 Standard or an IEEE 802.16 Standard, for example. While for simplicity the calibration station **502** is illustrated as having a single input/output port **526** connected to a single cable **522**, the calibration station **502** includes two or more input/output ports **526** connected to a corresponding number of cables **522** in other embodiments. Further, in some embodiments, the calibration station **502** is configured for wireless transmission and reception of communication signals. Although in embodiments in which the calibration station **502** is configured for wired transmission the input/output ports **526** are not connected to actual antennas, the input/output ports **526** are sometimes

referred to herein as "antenna ports," for ease of explanation. The wireless device **504** includes a plurality of input/output ports (or "antenna ports") **525**, according to an embodiment.

As shown in FIG. **5**, in an embodiment, the calibration system **500** includes the wireless device **504** being calibrated using the calibration system **500**. Referring to FIG. **1**, the wireless device **504** corresponds to the AP **14** or a portion of the AP **14**, such as the network interface **16** or the PHY processing unit **20** of the AP **14**, for example, in some embodiments. With continued reference to FIG. **1**, in some embodiments, the wireless device **504** corresponds to the client station **25-1** or a portion of the client station **25-1**, such as the network interface **27** or the PHY processing unit **29** of the client station **25-1**, for example. In other embodiments, the wireless device **504** corresponds to another suitable multiple antenna wireless communication device. The wireless device **504** includes a plurality of input/output ports (or "antenna ports") **525** corresponding to the multiple antennas of the device. In an embodiment, the wireless device **504** includes a calibration coefficient memory **518**. According to an embodiment, the calibration coefficient memory **518** is used to store the calibration coefficients determined by the calibration system **500** and is subsequently used by the wireless device **504** for RF chain imbalance compensation in an implicit beamforming technique. The calibration coefficient memory **518** corresponds to the memory **309** of FIG. **3**, or the memory **409** of FIG. **4**, in some embodiments.

One or more combiner/splitter units **520** are provided to connect multiple antenna ports of the wireless device **504** to one or more antenna ports of the calibration station **502**, in various embodiments and/or scenarios. In the embodiment of FIG. **5**, the calibration system **500** includes a single splitter/combiner unit **520** to connect four antenna ports **525** of the wireless device **504** to the single antenna port **526** of the calibration station **502**. The combiner splitter/combiner unit **520** includes a sum port **521** and four input/output ports **523**. Each of the input/output ports **523** is connected to an antenna port **525** of the wireless device **504** via a corresponding number of cables **524**. As illustrated, in the embodiment of FIG. **5**, the splitter/combiner unit **520** is a four way splitter/combiner having four input/output ports **523**. Accordingly, in this embodiment, the calibration system **500** is capable of calibrating a wireless device **504** having a maximum of four antenna ports **525**. In other embodiments, the splitter/combiner unit **520** includes any other suitable numbers (e.g., 2, 3, 5, 6, 7, 8, etc.) of input/output ports **521**. As an example, in an embodiment, the splitter/combiner **520** is a two-way splitter/combiner having two input/output ports **523**. Accordingly, in this embodiment, the calibration system **500** is capable of calibrating a wireless device **504** having a maximum of two antennas (or antenna ports **525**). As another example, in another embodiment, the splitter/combiner unit **520** is an eight way splitter/combiner and, in this embodiment, the calibration system **500** is capable of calibrating a wireless device **504** having a maximum of eight antennas (or antenna ports **525**). Further, in embodiments in which the calibration station **502** includes multiple antenna ports **526**, an additional splitter/combiner unit is provided to split the output of the splitter/combiner unit **520** among the multiple antenna ports of the calibration station **502**.

In embodiments in which the wireless device **504** communicates with the calibration station **502** via a wireless communication link, the combiner/splitter unit **520** is omitted from the calibration system **500**.

In the embodiment of FIG. **5**, the calibration station **502** includes a vector signal analyzer (VSA) **506** and a vector signal generator (VSG) **508**. In an embodiment, the VSA **506** receives and captures signals from the wireless device **504** when the calibration station **502** operates in a transmit mode, and the VSG **508** transmits signals to the wireless device **504** when the calibration when the calibration station **502** operates in a receive mode. To this end, in one embodiment, a switch **503** directs signals from the sum port **521** of the splitter/combiner unit **520** to an input port of the VSA **506** when the calibration station **502** is operating in a receive mode, or to an output port of the VSG **508** when the calibration station **502** is operating in a transmit mode, according to an embodiment. In an embodiment, the position of the switch **503** is controlled by the controller **510**, for example. In some embodiments, the switch **503** is omitted, and the cable **522** is manually switched between the output of the VSA **506** in receive mode and the output port of the VSG **508** in transmit mode.

In various embodiments, the controller **510** includes one or more network interfaces **512** for communicating with the calibration station **502** and the wireless device **504**. In the embodiment of FIG. **5**, the controller **512** includes a network interface **512-1** configured to interface with the calibration station **502** via a communication link **528** and a network interface **512-2** configured to interface with the wireless device **504** via a communication link **530**. Alternatively, in another embodiment, the network interface **512-1** and the network interface **512-2** are combined into a single network interface configured to interface with the calibration station **502** and the wireless device **504**. In various embodiments and/or scenarios, the communication link **528** is an RS 232 link, an Ethernet link, a universal serial bus (USB) link, or any other suitable communication link with which the calibration station **502** is configured to interface. Similarly, the communication link **530** is an RS-232 serial link, an Ethernet link, a universal serial bus (USB) link, or any other communication link suitable for interfacing with the wireless device **504**, according to various embodiments and/or scenarios. In one embodiment, the communication link **528** is a communication link separate from the communication link **530**. In another embodiment, the communication link **528** is the same communication link as the communication link **530**.

In an embodiment, the controller **510** includes a memory **514** and a processor **516**. In operation, the controller **510** obtains, from the calibration station **502**, information indicative of the communication channel from the WD **504** to the calibration station **502** ("forward" communication channel with respect to the WD **504**) and stores the forward channel information in the memory **514**, according to an embodiment. The controller **510** also obtains, from the WD **504**, information indicative of the communication channel from the calibration station **502** to the WD **504** ("reverse" communication channel with respect to the WD **504**) and stores the reverse channel information in the memory **514**. Then, based on the forward channel information obtained from the calibration station **502** and the reverse channel information obtained from the wireless device **504**, the processor **516** calculates calibration coefficients indicative of phase and/or amplitude imbalance between receive and transmit RF chains corresponding to each antenna port **525** of the wireless device **504**, according to an embodiment. In an embodiment, upon calculating calibration coefficients, the controller **510** communicates the calibration coefficients to the wireless device **504**. The wireless device **504** stores the calibration coefficients calculated by the controller **510** in a calibration coefficient memory **518**, according to an embodiment. The wireless device **504** subsequently utilizes the calibration coefficients stored in the calibration coefficient memory **518** when con-

ducting implicit beamforming, for example when operating in the WLAN **10** of FIG. **1**, in an embodiment.

FIGS. **6**A and **6**B are a flow diagrams illustrating an example calibration procedure **600** conducted by a calibration system, such as the calibration system **500** of FIG. **5**, according to an embodiment. The calibration procedure **600** will be described with reference to FIG. **7**, which is a timing diagram illustrating communications between a wireless device (e.g., the wireless device **504**) and a calibration station (e.g., the calibration station **502**), according to an embodiment. In an embodiment, the controller **510** initiates the calibration procedure **600** by transmitting a calibration initiation command to the wireless device **504**. In some embodiments, prior to transmitting the calibration initiation command, the controller **510** configures the calibration station **502** for receive mode operation. In one embodiment, for example, the controller **510** configures the calibration station **502** for receive mode operation by controlling the switch **503** to couple the antenna port **526** of the calibration station **502** to the VSA **506**, and instructs the VSA **506** to capture any signals received by the VSA **506** during a certain period of time.

At block **602**, the wireless device **504** transmits a sounding packet (e.g., a sounding packet **702**) to the calibration station **502**. In an embodiment, the sounding packet **702** is transmitted in response to a calibration initiation command that the WD **504** receives from the controller **510**. The sounding packet **702** travels in the "forward" communication channel with respect to the wireless device **504**, i.e., the communication channel from the wireless device **504** to the calibration station **502**. The sounding packet **702** includes training information based on which the forward channel can be estimated. In an embodiment, the sounding packet **702** is a null data packet (NDP) sounding packet. In some embodiments, transmission of the sounding packet **702** is preceded by transmission of a sounding announcement packet, such as an NDP announcement (NDPA) packet **701**.

At block **604**, the calibration station **502** receives the sounding packet **702**. The VSA **506** captures the sounding packet **702**, and generates, based on the sounding packet **702**, a channel descriptor indicative of the forward channel from the WD **504** to the calibration station **502**. In an embodiment, the VSA **506** generates the channel descriptor at block **604** by generating in-phase/quadrature-phase (I/Q) samples corresponding to the captured sounding packet **702**. In another embodiment, the VSA **506** generates the channel descriptor at block **604** by generating a channel estimation based on the captured sounding packet **702**. In yet another embodiment, VSA **506** generates the channel descriptor at block **604** by generating a steering matrix based on the captured sounding packet **702**. In general, the channel descriptor generated at block **604** includes any information indicative of the communication channel between the WD **504** and the calibration station **502**.

At block **606**, the calibration station **502** transmits the channel descriptor generated at block **604** to the controller **510**. At block **606**, the channel descriptor generated at block **604** is obtained by the controller **510**. At block **608**, the controller **510** verifies the channel descriptor obtained at block **606** to determine whether the channel descriptor is a valid channel descriptor, in some embodiments. If the controller **510** determines at block **610** that the channel descriptor received from the calibration station **502** at block **608** is not valid or contains errors, in an embodiment, blocks **602**-**606** are repeated, and the controller once again verifies validity of the channel descriptor at block **608**. Blocks **602**-**606** are repeated until a valid channel descriptor is obtained, according to one embodiment. Alternatively, in some embodiments, blocks **602**-**606** are repeated a certain number of times (e.g., ten times) to generate multiple (e.g., 10) channel descriptors, and the controller **510** then selects a valid channel descriptor from the multiple channel descriptors, or averages the multiple channel descriptors to generate a new channel descriptor. In any event, at block **610**, the controller **510** stores a first channel descriptor indicative of the forward channel from the WD **504** to the calibration station **502** in a memory, such as the memory **514**, for example. In some embodiments, block **608** is omitted, and block **606** is directly followed by block **610**, at which the channel descriptor obtained at block **606** is stored in memory.

Referring now to FIG. **6**B, the calibration procedure **600** continues at block **614**, at which the calibration station **502** transmits a sounding packet **704** to the WD **504**. The sounding packet **702** travels in the "reverse" communication channel with respect to the wireless device **504**, i.e., the communication channel from the wireless device **504** to the calibration station **502**. The sounding packet **704** includes training information based on which the reverse communication channel can be estimated. In an embodiment, the sounding packet **704** is a null data packet (NDP) sounding packet. In some embodiments, transmission of the sounding packet **704** is preceded by transmission of a sounding announcement packet, such as an NDP announcement (NDPA) packet **703**.

In an embodiment, prior to transmission of the sounding packet **704**, the controller **510** configures the calibration station **502** for transmit mode. In one embodiment, for example, the controller **510** configures the calibration station **502** for transmit mode operation by controlling the switch **503** to couple the antenna port **526** of the calibration station **502** to the VSG **508**. The controller **510** then controls the VSG **508** to transmit the sounding packet **704** and, in some embodiments, the sounding announcement packet **703**.

The sounding packet **704** and the sounding announcement packet **703**, in an embodiment, are generated to allow the WD **504** to conduct channel estimation in accordance with sounding procedures defined by the communication protocol being utilized for the calibration procedure **600**. In some embodiments, the packets **703**, **704** are generated externally with respect to the VSG **508**. In one such embodiment, for example, a simulation software that simulates operation of the wireless device **504** is utilized. In another embodiment, a signal analyzer, such as the VSA **506** is used to capture a sounding packet and/or a sounding announcement packet generated by a reference wireless device, and the sounding packet **704** and/or the sounding announcement packet **703** is generated based on the corresponding captured packet. The reference wireless device is the wireless device **504**, or a different wireless device configured to operate according to the communication protocol being utilized, in some embodiments. In any event, the packets generated externally with respect to the VSG **508**, in an embodiment, are then provided to the VSG **508** (e.g., by providing I/Q samples corresponding to the sounding announcement packet **703** and/or the sounding packet **704**) and used by the VSG **508** at block **614** to transmit the sounding packet to the WD **504**. In some embodiments, the VSG **508** is capable of generating the packets **703**, **704** internally, for example by using software provided with the VSG **508** (or with the calibration station **502**) and in such embodiments, external generation of the packets **703**, **704** is not required.

In some embodiments, the wireless device **504** is configured to receive and interpret a sounding packet only if the sounding packet is intended for the wireless device **504** and/or if the sounding packet is transmitted by a particular transmitting wireless device or devices, such as an access point or

several access points with which the wireless device **504** is associated, as indicated by the preceding sounding announcements packet, for example. In such embodiments, the wireless device **504** discards the sounding packet **704** if the preceding announcement packet **703** does not include a particular device address (or particular device addresses). Accordingly, to ensure that the WD **504** processes the sounding packet **704**, the announcement packet **703** includes a physical address (e.g., a MAC address) associated with the wireless device **504** and/or a physical address (e.g., a MAC address) associated with the calibration station **502** (and/or with VSG **508**). For example, the controller **510** configures the wireless device **504** with a particular MAC address, and provides this MAC address to the entity generating the announcement packet **703** for inclusion in the announcement packet **703**. Similarly, the controller **510** configures the calibration station **502** (or the VSG **508**) with a particular MAC address and configures the wireless device **504** to process sounding packets associated with the MAC address of the calibration station **502** (or the VSG **508**). The controller **510** then provides the MAC address of the calibration station **502** (or the VSG **508**), in addition to or instead of the MAC address associated with the wireless device **504**, to the entity generating the announcement packet **703** for inclusion in the announcement packet **703**.

At block **616**, the WD **504** receives the sounding packet **704** and generates a channel descriptor of the reverse channel from the calibration station **502** to the wireless device **504**. In one embodiment, the channel descriptor generated at block **616** includes I/Q samples of the sounding packet **704**. In another embodiment, the channel descriptor generated at block **616** includes a channel estimation generated by the WD **504** based on the sounding packet **704**. As another example, in another embodiment, the channel descriptor generated at block **616** includes a steering matrix generated by the WD **504** based on the sounding packet **704**. In other embodiments, other suitable information indicative of the reverse channel from the calibration station **502** to the wireless device **504** is generated at block **616**.

At block **618**, the controller **510** obtains the channel descriptor generated at block **618** from the wireless device **504**. In some embodiments, at block **620**, the controller **510** verifies the channel descriptor received at block **618** to determine whether the channel descriptor is a valid channel descriptor. If the controller **510** determines at block **620** that the channel descriptor received from the calibration station **502** at block **618** is not valid or contains errors, in an embodiment, blocks **614-618** are repeated, and the controller once again verifies validity of the channel descriptor at block **620**. The controller **510** repeats blocks **614-618** until a valid channel descriptor is received, according to an embodiment. Alternatively, in some embodiments, blocks **614-618** are repeated a certain number of times (e.g., ten times) to generate multiple (e.g., 10) channel descriptors, and the controller **510** then selects a valid channel descriptor from the multiple channel descriptors, or averages the multiple channel descriptors to generate a new channel descriptor. In any event, at block **622**, the controller **510** stores a second channel descriptor indicative of the channel from the calibration station **502** to the WD **504** in the memory **514**. In some embodiments, block **620** is omitted and the controller **510** simply stores the second channel descriptor obtained at block **618** in memory at block **622**.

At block **624**, based on the first channel descriptor stored in memory at block **610** and the second channel descriptor stored in memory at block **622**, the controller **510** calculates calibration coefficients indicative of phase and/or amplitude imbalance between transmit and receive RF chains in the wireless device **504**. In an embodiment, calibration coefficients calculated at block **624** correspond to elements of a correction matrix, such as, for example, the correction matrix $K_{A,Tx}$ or the correction matrix $K_{A,Rx}$ discussed above. Several example methods for calculating calibration coefficients, according to some embodiments, are discussed in greater detail below in connection with FIGS. **8-10** and Equations 9-21. At block **626**, the controller sends calibration coefficients generated at block **626** are sent to the wireless device **504**.

FIG. **8** is a flow diagram of an example method **800** for generating calibration coefficients based on an estimate of the forward channel H_{AB}, or the channel from the wireless device **504** to the calibration station **502**, and an estimate of the reverse channel H_{BA}, or the channel from the calibration station **502** and the wireless device **504**, according to an embodiment. In an embodiment, the controller **510** performs the method **800** to calculate calibration coefficients at block **624** (FIG. **6**B). In this method, calibration coefficients correspond to elements of a diagonal matrix $K_{A,Tx}$.

At a block **802**, for each port at the calibration station **502**, a corresponding calibration coefficient corresponding to the i-th port of the wireless device **540** is calculated based on the i-th row in $\tilde{H}_{AB}$ and the i-th row in $\tilde{H}_{BA}{}^{T}$. The k-th element of the i-th row in $\tilde{H}_{AB}$ can be written as:

$$[\tilde{H}_{AB}]_{ki}=c_{B,Rx_i}[H_{AB}]_{ik}c_{A,Tx_k}, \quad \text{(Equation 9)}$$

Similarly, the k-th element of the i-th row of $\tilde{H}_{BA}{}^{T}$ is the k-th element of the i-th column of $\tilde{H}_{BA}$, which can be written as:

$$[\tilde{H}_{BA}]_{ki}=c_{A,Rx_k}[H_{AB}]_{ik}c_{B,Tx_i}, \quad \text{(Equation 10)}$$

The (k,k) element of the diagonal correction matrix $K_{A,Tx}$ corresponding to i is then determined as:

$$[K_{A,Tx}]_{kk}=\frac{[\tilde{H}_{BA}]_{ki}}{[\tilde{H}_{AB}]_{ik}}=\left(\frac{c_{B,Tx_i}}{c_{B,Rx_i}}\right)\frac{c_{A,Rx_k}}{c_{A,Tx_k}}=\alpha\frac{c_{A,Rx_k}}{c_{A,Tx_k}}, \quad \text{(Equation 11)}$$

where

$$\alpha=\frac{c_{B,Tx_i}}{c_{B,Rx_i}}, \quad \text{(Equation 12)}$$

Thus, for example, the (1,1) element of $K_{A,Tx}$ corresponding to i is determined as:

$$[K_{A,Tx}]_{11}=\frac{[\tilde{H}_{BA}]_{1i}}{[\tilde{H}_{AB}]_{i1}}=\left(\frac{c_{B,Tx_i}}{c_{B,Rx_i}}\right)\frac{c_{A,Rx_1}}{c_{A,Tx_1}}=\alpha\frac{c_{A,Rx_1}}{c_{A,Tx_1}}, \quad \text{(Equation 13)}$$

Similarly, the (2,2) element of $K_{A,Tx}$ corresponding to i is determined as:

$$[K_{A,Tx}]_{22}=\frac{[\tilde{H}_{BA}]_{2i}}{[\tilde{H}_{AB}]_{i2}}=\alpha\frac{c_{A,Rx_2}}{c_{A,Tx_2}}, \quad \text{(Equation 14)}$$

As can be seen from Equations 11-14, $\hat{H}_{AB}=\tilde{H}_{AB}K_{A,Tx}=\alpha C_{B,Rx}H_{AB}C_{A,Rx}=\alpha D_B\tilde{H}_{BA}{}^{T}$,
where $D_B=C_{B,Rx}C_{B,Tx}{}^{-1}$, and the calibrated channels are semi-reciprocal.

At a block **804**, the correction matrix $K_{A,Tx}$ is generated based on the i estimates generated at the block **802**. As just

one example, in one embodiment, the correction matrix $K_{A,Tx}$ is generated based on an average of the i estimates. For instance, in this embodiment, the (1,1) element is generated as an average of the i estimates of the (1,1) element generated at the block **804**. Similarly, the (2,2) element is generated as an average of the i estimates of the (2,2) element generated at the block **804**, etc.

In an embodiment, the controller **510** or the wireless device **504** calculates the correction matrix $K_{A,Rx}$ by inverting the correction matrix $K_{A,Tx}$. Alternatively, the correction matrix $K_{A,Rx}$ is calculated according to a method similar to the method **800** and equations similar to Equations 11 and 12, in some embodiments. In some such embodiments, the correction matrix $K_{A,Tx}$ is then calculated by inverting the correction matrix $K_{A,Rx}$.

In some examples, block **802** determines only the phase mismatch in calculating the correction matrix $K_{A,Tx}$, for example by averaging over different antenna index i or over different OFDM sub-carriers. In such examples, the correction matrix $K_{A,Tx}$ is expressed as a phase correction factor where the phase difference between the reverse estimation channel and the forward estimation channel is determined to provide the phase difference for each antenna port k of a wireless device (e.g., wireless device **504**):

$$[K_{A,Tx}]_{kk}=\exp\{j(\angle[\tilde{H}_{BA}]_{ki})\},\forall i \quad \text{(Equation 15)}$$

FIG. **9** is a flow diagram of another example method **900** for generating a correction matrix based on the estimation of the reverse channel $\tilde{H}_{BA}$ and the estimation of the forward channel $\tilde{H}_{AB}$, according to another embodiment. In an embodiment, the controller **510** performs the method **900** to calculate a correction matrix at block **624** (FIG. **6**B). In this method, it is assumed that the correction matrix $K_{A,TX}$ is a diagonal matrix.

Block **902** determines the singular matrixes that define the estimate of the forward channel $\tilde{H}_{AB}$ and the estimate of the reverse channel $\tilde{H}_{BA}$. A singular value decomposition (SVD) method or any other method or technique that determines a set of right singular matrixes that accurately describes or defines the forward channel $\tilde{H}_{AB}$ and another set of right singular matrixes that accurately describes or defines the estimate of the reverse channel $\tilde{H}_{BA}$ may be used. Or, in other examples, the estimate of the reverse channel $\tilde{H}_{BA}{}^{T}$ is determined from inverting the estimate of the forward channel $\tilde{H}_{AB}$. A block **904** then determines a forward steering matrix, V_F, using a method f, and a reverse steering matrix, V_R, using the same method f and computes the correction matrix using:

$$V_F=f(\tilde{H}_{AB}) \quad \text{(Equation 16)}$$

$$V_F=f(\tilde{H}_{BA}{}^{T}) \quad \text{(Equation 17)}$$

Block **906** then determines the correction matrix based on the determined forward and backward steering matrices, according to:

$$K_{A,Tx}=V_F V_R{}^{H}, \quad \text{(Equation 18)}$$

In some examples, the diagonal of the calculated correction matrix is made to correspond to pure phase shifts by normalization. For example, the block **906** may express the correction matrix with phase correction only by applying the mathematical formula:

$$K_{A,Tx}=\exp\{j\angle(V_F V_R{}^{H})\} \quad \text{(Equation 19)}$$

While the foregoing describes determining the correction matrix $K_{A,Tx}$, the correction matrix $K_{A,Rx}$ can be calculated instead, e.g., by inverting the correction matrix $K_{A,Tx}$ determined using Equations 14, 15, 18, or 19. Alternatively, the correction matrix $K_{A,Rx}$ is calculated first according to equations similar Equations 12-19. Then, the correction matrix $K_{A,Tx}$ is calculated by inverting the correction matrix $K_{A,Rx}$.

FIG. **10** illustrates an example approach **1000** to the method **900**, and is achieved by the blocks **904** and **906** in FIG. **9**, in some embodiments. Specifically, the block **904** determines the forward steering matrix, V_F, and the reverse steering matrix, V_R, using a cophasing technique. A block **1002** selects one antenna port index i corresponding to an antenna port of a calibration station (Station B). For example, the controller **510** selects the index i corresponding to the Station B antenna port with the strongest indicated channel gain from the estimation of the forward channel $\tilde{H}_{AB}$. In another example, the controller **510** selects the antenna port index i based on row averages. Block **1002** then generates partial estimations of forward and reverse channels $[\tilde{H}_{AB}]_{*i}$ and $[\tilde{H}_{BA}{}^{T}]_{*i}$, respectively.

With the generated partial estimates of the forward and reverse channels, block **1004** determines the forward steering matrix V_F by taking a cophasing of the partial estimation $[\tilde{H}_{AB}]_{*i}$, as indicated by:

$$V_F=\text{cophase}\left([\tilde{H}_{AB}]_{i^*}\right)= \quad \text{(Equation 20)}$$

$$\text{cophase}\left([h_{i1}^{(F)}h_{i2}^{(F)}\ \ldots\ h_{iN_{Tx}}^{(F)}]\right)=\begin{bmatrix} e^{j\theta_{NTx}1} \\ e^{j\theta_{NTx}2} \\ \vdots \\ 1 \end{bmatrix}.$$

The block **1004** also determines the reverse steering matrix V_R by taking a cophasing of the partial estimation $[\tilde{H}_{BA}{}^{T}]_{*i}$, as indicated by:

$$V_R=\text{cophase}\left([\tilde{H}_{BA}^{T}]_{i^*}\right)= \quad \text{(Equation 21)}$$

$$\text{cophase}\left([h_{i1}^{(R)}h_{i2}^{(R)}\ \ldots\ h_{iN_{Tx}}^{(R)}]\right)=\begin{bmatrix} e^{j\Psi_{NTx}1} \\ e^{j\Psi_{NTx}2} \\ \vdots \\ 1 \end{bmatrix}.$$

Because block **1002** identifies only a single receive antenna, the channel estimate is reduced to a single row, leaving each of V_F and V_R as linear matrices. Block **1006** produces the correction matrix $K_{A,Tx}$ by applying Equation 18, In this example approach, the correction matrix $K_{A,Tx}$ represents the phase difference between each of the corresponding forward and reverse steering matrices:

$$K_{A,Tx}=V_F V_R^{H}=\begin{bmatrix} e^{j(\theta_{NTx}1-\Psi_{NTx}2)} & & \\ & e^{j(\theta_{NTx}2-\Psi_{NTx}2)} & \\ & & \ddots \\ & & 1 \end{bmatrix}$$

FIG. **11** is a flow diagram of an example method **1100** for calibrating a wireless communication device, according to an embodiment. With reference to FIG. **5**, the method **1100** is performed by the calibration system **500**, in an embodiment. For example, the controller **510**, the calibration station **502**, and the wireless device **504** perform various steps of the method **1100**, according to an embodiment. Referring now to

FIG. **1**, the method **1100** is used for calibrating the AP **14** or the client station **25-1**, in an embodiment. In other embodiments, the method **1100** is performed by other suitable calibration systems and/or is used to calibrate other suitable communication devices.

At block **1102**, a first sounding packet is transmitted. The first sounding packet is directed from a wireless device to a calibration station. Transmission of the first sounding packet is initiated by a controller communicatively coupled to the wireless device and the calibration station, in an embodiment. In one embodiment, the sounding packet **702** of FIG. **7** is transmitted. In another embodiment, another suitable sounding packet is transmitted. In some embodiments, transmission of the first sounding packet is preceded by a transmission of a sounding announcement packet, such as an NDPA packet, for example. At block **1104**, the first sounding packet is received by the calibration station (e.g., by a VSA included in the calibration station). Upon receiving the first sounding packet, the calibration station generates a first channel descriptor based on the first sounding packet. The first channel descriptor generated at block **1104** includes any suitable information indicative of the communication channel from the wireless device to the calibration station (the forward communication channel with respect to the wireless device). In one embodiment, the first channel descriptor includes I/Q samples of the first sounding packet, for example. As another example, in another embodiment, the first channel descriptor includes a channel matrix generated based on training information included in the first sounding packet. In other embodiments, the first channel descriptor includes other suitable information representative of the forward communication channel, such as a steering matrix calculated based on a channel estimate of the forward communication channel, for example.

At block **1106**, a second sounding packet is transmitted. The second sounding packet is directed from the calibration station to the wireless device. The second sounding packet is directed from the calibration station to the wireless device. Transmission of the second sounding packet is initiated by a controller communicatively coupled to the wireless device and the calibration station, in an embodiment. In one embodiment, the sounding packet **704** of FIG. **7** is transmitted. In another embodiment, another suitable sounding packet is transmitted. In some embodiments, transmission of the first sounding packet is preceded by a transmission of a sounding announcement packet, such as an NDPA packet, for example. At block **1108**, the second sounding packet is received by the wireless device. Also at block **1108**, the wireless device generates a second channel descriptor based on the second sounding packet. The second channel descriptor includes any suitable information indicative of the communication channel from the calibration station to the wireless device (the reverse communication channel with respect to the wireless device). As an example, in one embodiment, the second channel descriptor includes I/Q samples of the second sounding packet, for example. In another embodiment, the second channel descriptor includes a channel estimation generated based on training signals included in the second sounding packet. As just another example, in another embodiment, the second channel descriptor includes a steering matrix calculated based on the channel estimate of the reverse communication channel.

At block **1110**, the first channel descriptor generated at block **1104** and the second channel descriptor generated at block **1108** are obtained at the controller. At block **1112**, the controller generates, based on the channel descriptors obtained at block **1110**, calibration coefficients indicative of a magnitude and/or phase imbalances between transmit and receive RF chains in the wireless device. The calibration coefficients are generated at block **1112** using any suitable method for generating calibration coefficients based on information indicative of a forward channel and a reverse communication channel relative to a communication device. As an example, in one embodiment, the calibration coefficients are generated at block **1112** in accordance with the method **800** of FIG. **8**. As another example, in another embodiment, the calibration coefficients are generated at block **1112** in accordance with the method **900** of FIG. **9**, or with the method **1000** of FIG. **10**.

At block **1114**, the controller sends the calibration coefficients generated at block **1112** to the wireless communication device being calibrated. In an embodiment, the wireless communication device stores the correction matrix in a memory and subsequently utilizes the correction matrix when conducting implicit beamforming when communication with another wireless device, such as when operating in the WLAN **10** of FIG. **1**, for example.

At least some of the various blocks, operations, and techniques described above may be implemented utilizing hardware, a processor executing firmware instructions, a processor executing software instructions, or any combination thereof.

When implemented in hardware, the hardware may comprise one or more of discrete components, an integrated circuit, an application-specific integrated circuit (ASIC), a programmable logic device (PLD), etc.

When implemented utilizing a processor executing software or firmware instructions, the software or firmware instructions may be stored in any computer readable memory such as on a magnetic disk, an optical disk, or other storage medium, in a RAM or ROM or flash memory, processor, hard disk drive, optical disk drive, tape drive, etc. Likewise, the software or firmware instructions may be delivered to a user or a system via any known or desired delivery method including, for example, on a computer readable disk or other transportable computer storage mechanism or via communication media. Communication media typically embody computer readable instructions, data structures, program modules or other data in a modulated data signal such as a carrier wave or other transport mechanism. The term "modulated data signal" means a signal that has one or more of its characteristics set or changed in such a manner as to encode information in the signal. By way of example, and not limitation, communication media includes wired media such as a wired network or direct-wired connection, and wireless media such as acoustic, radio frequency, infrared and other wireless media. Thus, the software or firmware instructions may be delivered to a user or a system via a communication channel such as a telephone line, a DSL line, a cable television line, a fiber optics line, a wireless communication channel, the Internet, etc. (which are viewed as being the same as or interchangeable with providing such software via a transportable storage medium). The software or firmware instructions may include machine readable instructions that, when executed by the processor, cause the processor to perform various acts.

While the present invention has been described with reference to specific examples, which are intended to be illustrative only and not to be limiting of the invention, changes, additions and/or deletions may be made to the disclosed embodiments without departing from the scope of the invention. For example, one or more portions of methods or techniques described above may be performed in a different order (or concurrently) without altering the principles of the present disclosure.

What is claimed is:

1. A method of calibrating a wireless communication device, the method comprising:

generating, at a calibration station, a first channel descriptor based on a first sounding packet received, at the calibration station, from the wireless communication device via a first radio frequency (RF) communication channel from the wireless communication device to the calibration station, the first channel descriptor corresponding to the first RF communication channel;

transmitting, with the calibration station, a second sounding packet via a second RF communication channel from the calibration station to the wireless communication device;

obtaining, at a processor device, the first channel descriptor;

obtaining, at the processor device, a second channel descriptor corresponding to the second RF communication channel, wherein

the second channel descriptor was generated, at the wireless communication device, based on the second sounding packet, and

the second channel descriptor was obtained, from the wireless communication device, via a communication link separate from the second RF communication channel;

generating, using the processor device and based on the first channel descriptor and the second channel descriptor, calibration coefficients indicative of one or both of (i) phase imbalance between a receive RF chain and a transmit RF chain at the wireless communication device, and (ii) amplitude imbalance between the receive RF chain and the transmit RF chain at the wireless communication device; and

sending the calibration coefficients from the processor device to the wireless communication device so that the wireless communication device can use the calibration coefficients to compensate for the one or both of (i) the phase imbalance between the receive RF chain and the transmit RF chain, and (ii) the amplitude imbalance between the receive RF chain and the transmit RF chain at the wireless communication device.

2. The method of claim 1, wherein:

the communication link is a first communication link between the processor device and the wireless communication device; and

obtaining the first channel descriptor comprises obtaining the first channel descriptor via a second communication link between the processor device and the calibration station.

3. The method of claim 1, wherein:

the communication link is a wired communication link.

4. The method of claim 3, wherein:

the wired communication link is a first wired communication link between the processor device and the wireless communication device;

sending the calibration coefficients from the processor device to the wireless communication device comprises sending the calibration coefficients via the first wired communication link; and

obtaining the first channel descriptor comprises obtaining the first channel descriptor via a second wired communication link between the processor device and the calibration station.

5. The method of claim 1, further comprising using the processor device to:

prompt the wireless communication device to transmit the first sounding packet, and

prompt the calibration station to transmit the second sounding packet.

6. The method of claim 1, further comprising:

receiving the first sounding packet at a vector signal analyzer included in the calibration station.

7. The method of claim 1, wherein transmitting the second sounding packet from the calibration station comprises transmitting the second sounding packet from a vector signal generator included in the calibration station.

8. The method of claim 1, wherein the second sounding packet is generated using software, executing on a processor device of a signal generator, that simulates operation of the wireless communication device.

9. The method of claim 1, wherein the second sounding packet is generated at least by:

using a vector signal analyzer (VSA) to capture a sounding packet transmitted by (i) the wireless communication device or (ii) another wireless communication device;

generating in-phase/quadrature phase (I/Q) samples corresponding to the captured sounding packet; and

generating the sounding packet using the I/Q samples.

10. The method of claim 1, wherein the second sounding packet is a null data packet (NDP) sounding packet.

11. The method of claim 10, further comprising:

receiving, at the calibration station, a first NDP announcement (NDPA) packet prior to receiving the first sounding packet; and

transmitting, with the calibration station, a second NDPA packet prior to transmitting the second sounding packet.

12. The method of claim 11, wherein the second NDPA includes one or both of (i) a medium access control (MAC) address associated with the wireless communication device and (ii) a medium access control (MAC) address associated with the calibration station.

13. The method of claim 1, wherein:

the communication link is a first wired communication link;

transmitting the first sounding packet comprises transmitting the first sounding packet via a second wired communication link between the wireless communication device and the calibration station; and

transmitting the second sounding packet comprises transmitting the second sounding packet via the second wired communication link.

14. The method of claim 13, wherein:

the second wired communication link includes a power splitter/combiner unit;

transmitting the first sounding packet via the second wired communication link comprises transmitting the first sounding packet via the power splitter/combiner unit; and

transmitting the second sounding packet via the second wired communication link comprises transmitting the second sounding packet via the power splitter/combiner unit.

15. A calibration system, comprising:

a calibration station configured to:

generate a first channel descriptor based on a first sounding packet received, at the calibration station, from a wireless communication device via a first wireless communication channel from the wireless communication device to the calibration station, the first channel descriptor corresponding to the first wireless communication channel, and

transmit a second sounding packet to the wireless communication device via a second wireless communication channel from the calibration station to the wireless communication device; and

a processor device separate from the wireless communication device, the processor device communicatively coupled to the wireless communication device via a communication link separate from the second wireless communication channel, the processor device configured to

obtain the first channel descriptor,

obtain a second channel descriptor via the communication link, wherein the second channel descriptor was generated by the wireless communication device based on the second sounding packet,

generate, based on the first channel descriptor and the second channel descriptor, calibration coefficients indicative of one or both (i) phase imbalance between a receive radio frequency (RF) chain and a transmit RF chain at the wireless communication device, and (ii) amplitude imbalance between the receive RF chain and the transmit RF chain at the wireless communication device, and

send the calibration coefficients from the controller to the wireless communication device so that the wireless communication device can use the calibration coefficients to compensate for the one or both of (i) the phase imbalance between the receive RF chain and the transmit RF chain, and (ii) the amplitude imbalance between the receive RF chain and the transmit RF chain at the wireless communication device.

16. The calibration system of claim **15**, wherein:

the communication link is a first communication link between the processor device and the wireless communication device; and

obtaining the first channel descriptor comprises obtaining the first channel descriptor via a second communication link between the processor device and the calibration station.

17. The calibration system of claim **15**, wherein:

the communication link is a wired communication link.

18. The calibration system of claim **17**, wherein:

the wired communication link is a first wired communication link between the processor device and the wireless communication device; and

the calibration station is configured to transmit the second sounding packet via a second wired communication link between the calibration station and the wireless communication device.

19. The calibration system of claim **18**, wherein the second wired communication link includes a power splitter/combiner unit coupled i) to the calibration station, and ii) to the wireless communication device.

20. The calibration system of claim **15**, wherein the processor device is further configured to prompt the calibration station to transmit the second sounding packet.

21. The calibration system of claim **15**, wherein the calibration station comprises one or more vector signal analyzers and one or more vector signal generators.

22. The calibration system of claim **21**, wherein the calibration station is configured to receive the first sounding packet at each of the one or more vector signal analyzers included in the calibration station.

23. The calibration system of claim **21**, wherein the calibration station is configured to transmit the second sounding packet from each of the one or more vector signal generators included in the calibration station.

24. The calibration system of claim **15**, wherein:

the calibration station includes a signal generator having a processor; and

the second sounding packet is generated using software, executed by the processor of the signal generator, that simulates operation of the wireless communication device.

25. The calibration system of claim **15**, wherein the calibration station includes:

a vector signal analyzer (VSA) configured to

capture i) the first sounding packet or a third sounding packet transmitted by the wireless communication device, or ii) a fourth sounding packet transmitted by another wireless communication device, and

generate in-phase/quadrature phase (I/Q) samples corresponding to the captured sounding packet; and

a signal generator configured to generate the second sounding packet using the I/Q samples.

26. The calibration system of claim **15**, wherein the second sounding packet is a null data packet (NDP) sounding packet.

27. The calibration system of claim **15**, wherein the calibration station is further configured to transmit an NDP announcement (NDPA) packet prior to transmitting the second sounding packet.

28. The calibration system of claim **27**, wherein the NDPA includes one or both of (i) a medium access control (MAC) address associated with the wireless communication device and (ii) a medium access control (MAC) address associated with the calibration station.

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